

On the Occurrence Conservation and
Utilization of Water Resources as Related
to Physiographic Features with Especial
Reference to California

INAUGURALDISSERTATION

zur

Erlangung der philosophischen Doktorwürde

vorgelegt der

Philosophisch-naturwissenschaftlichen Fakultät
der Universität Basel

von

JOHN ZAHLÉN

aus San Francisco (Calif., U. S. A.)



UPPSALA 1938

ALMQVIST & WIKSELLS BOKTRYCKERI-A.-B.

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Genehmigt von der philosophisch-naturwissenschaftlichen
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Prof. M. Reinhard
Dekan



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FOREWORD

The present study is based upon my own observations made during more than ten years activity on hydro-electric development in the Sierra Nevada and the Cascade Mountains, and upon the published results of studies made by Federal and State Government Agencies, as well as by power companies, consulting engineers, and by water users associations. Several winter seasons were spent in residence at construction camps on the western slope of the mountain chain whereby an excellent opportunity was offered to observe snow-rainfall and runoff conditions. Many thousand kilometers were covered afoot and by automobil to all parts of the State in visiting projects and structures pertaining to hydraulic developments.

The available literature pertaining to the subject studied has been freely drawn upon for information and data. To be mentioned are especially the publications of: The United States Geological Survey, Bulletins, Water-Supply Papers, Professional Papers, and Annual Reports; the United States Department of Agriculture, Bulletins and Technical Bulletins; the Federal Power Commission; the United States Weather Bureau; the National Resources Board. The publications of the California State Department of Public Works, Division of Engineering and Irrigation, and of the Division of Water Resources, as well as those of the California State Mining Bureau, Geologic Branch, were studied. The publications of the Departments of Geology, and of Geography University of California, and of Leland Stanford Jr., University, were consulted. Many articles in Geographical Review, Economic Geography, Economic Geology, Science, and numerous other Periodicals have been of aid.

The author obtained literature through, or was extended courtesies by the Public Library of the City and County of San Francisco, Mechanics Institute Library, State Mining Bureau Library, Standard Oil Library, Leland Stanford Jr. University Library, California State Library at Sacramento, and its Sutro Branch at San Francisco. Valuable information and memoranda were obtained through the offices of Mr. H. D. McGlashan, District Engineer U. S. Geological Survey; Mr. E. W. Kramer, District Engineer, Federal Power Commission, both of San Francisco; Mr. A. D. Ed-

monston, Deputy State Engineer in Charge of Investigation of Water Resources; Mr. G. W. Hawley, Deputy State Engineer in Charge of Dams. The Pacific Gas and Electric Company, San Francisco, the Los Angeles County Flood Control District, the Los Angeles Metropolitan Water District, supplied data on power developments and domestic water supply. The United States Bureau of Reclamation furnished data on the Boulder Dam and the All-American Canal projects. In addition various water companies and water users organizations gave data on irrigation. Professional geographers, geologists and engineers made valuable suggestions.

Basle, Switzerland.

March 1938.

J. V. Z.

PART ONE

Geography and Geology as Related to Problems in Development of Water Power, Public Water Supply, and Irrigation.

I. Geography.

In the following general discussion of geography as related to problems in the development of water resources for water power, public water supply and irrigation, the field of water power has received more attention than either public water supply or irrigation as it represents the wider application of the principles involved. Practically every phase of water problems as regards collection, storage, conveyance, etc. that is encountered in public water supply and irrigation development, with the exception of problems of pumping from underground sources, are generally met with in the development of water power.

Water power is derived from the conversion of the energy of falling water into mechanical work. If a volume of water is situated at a certain height above plane of reference it possesses a potential energy proportionate to the product of these two factors; of weight and height. All of this potential energy can be converted into kinetic energy by allowing the water to fall through the height it possesses above the plane of reference. If the water in falling passes through a suitable hydraulic motor most of its potential energy can be converted into useful mechanical work in which case the water will reach the bottom of the fall with little or no energy remaining instead of having its full energy remaining in kinetic form as it would do if it fell freely and unrestricted. In practice water power is usually derived from running streams and the amount of water is expressed in terms of the rate at which energy is supplied to or derived from the hydraulic motor. The ratio of the rate at which energy is derived from an hydraulic motor to that at which it is supplied to the motor is called the "efficiency" of the motor. The amount of power may be expressed in terms of the rate at which energy is supplied or the rate at which mechanical work can be performed by the motor. The former is called the "theoretical power" of the water or stream supplying the motor.

One horse power, as defined by Watt, represents energy sufficient to raise a weight of 33,000 pounds one foot high per minute, or in other words, 33,000 foot-pounds per minute or 550 foot-pounds per second. Fresh water weighs 62.42 pounds per cubic foot, hence the theoretical horse power of a constant stream of water flowing in a volume of q cubic feet per second and falling through a height of h feet is equal to $62.42 \cdot q \cdot h / 550$ horse power. This reduces to the simple rule: Theoretical horse power of water

$0.1135 \cdot q \cdot h$ in English units. When using the metric system the height of fall is generally expressed in meters and the volume of water in cubic meters per second the weight of one cubic meter of fresh water being 1,000 kilogram. The cheval-vapeur or metric horse power having been established at 75 kilogram-meters per second the theoretical horse power of a constant stream of water flowing in a volume of Q cubic meters per second and falling through a height of H meters is equivalent to: $1,000 \cdot Q \cdot H/75$ horse power. This reduces to the simple rule: Theoretical horse power of water $13.333 \cdot Q \cdot H$.

The output or derived power of an hydraulic motor or of a water power is the product of the theoretical power multiplied by the efficiency expressed as a decimal or if the efficiency is E then the mechanical or brake horse power is equal to $0.1135 \cdot q \cdot h \cdot E$ in English units, or equal to: $13.333 \cdot Q \cdot H \cdot E$ in metric units. The metric horse power is smaller than the horse power in English units so that: 1 hp (Engl.) = 1.0139 metric, or 1 hp (metric) = 0.9863 Engl.

Efficiency may be considered with reference to the entire power plant including allowances for losses of power in electric generators and other equipment in the case of hydroelectric plants. If used in the latter sense it is termed "overall efficiency" and the theoretical horse power multiplied by the over-all efficiency represents the net rate of power output by the plant or power development.

The following Table 1 shows the average efficiency and the best efficiency ordinarily obtained from various types of hydraulic motors. It shows for purposes of comparison the efficiency of various early types of water-wheels, such as current, flutter and center discharge wheels. Even these were more efficient than the best fuel engines today. At the present time practically all water wheels in use are of one or the other of the last three types. These have efficiencies ranging from 70 to 94 per cent. A developed water power is the most efficient means of converting natural energy into mechanical work and the hydraulic turbine is the simplest of all prime movers. Such a water wheel usually contains only one continuously moving part—the runner.

Table 1. Average efficiencies and best efficiencies for various types of hydraulic motors (Horton, 1929):

Simple current wheel	15 %	25 %
Primitive vertical Flutter wheel	10	20
Same with curved vanes	15	25
Wooden Undershot wheel	30	40
Poncelet Undershot wheel	50	60
Breast wheel	50	65
Overshot wheel	60	85
Scroll Central Discharge and Tub wheels	20	50
Jonval Type Turbine Stock Pattern	60	70
Fourneyron Turbine	70	85
Early American Type Turbine	60	70
Better Class American Type Turbine	75	92.5
Francis Type High Head Turbine	75	94
Pelton Type Impulse Turbines	80	92.5

Over-all efficiencies for hydroelectric plants working near capacity output conditions cover a wide range, typical data for some California plants being as follows (Bonner, 1928):

Reaction Type		Impulse Type	
High	83.7 %	High	76.4 %
Low	73.0	Low	63.1
Average ^a (15 plants)	77.1	Average (15 plants)	70.8

In the following the geographical conditions as related to the development of water power, chiefly, will be discussed together with the physical and economic circumstances which influenced the establishment and expansion of the hydroelectric and related industries in some localities or regions in preference to others.

From the physical viewpoint there are two outstanding factors susceptible of combination in a variety of ways—water and fall. The weight of a certain quantity of water falling down through a height puts in motion a hydraulic motor. The greater the quantity of water available and the higher the fall the more energy generated. The most favorable conditions for the hydraulic industry will then be realized in regions of pronounced mountainous character which at the same time are well supplied with water, regions of humid climate. Switzerland, Norway, the West Coast of North America, are examples of favored parts of the world in respect to water power resources.

However, as the quantity of water is a factor of prime importance, its steady falling, its duration, regularity of regimen, is of utmost importance. A river with a marked variation in flow is of inferior value in its natural state for utilization must be based on minimum flow or power production will be irregular. Obviously it is possible to correct irregularity of flow by the construction of storage reservoirs and this has become an outstanding feature of water conservation not only for power generation but also for irrigation, public water supply and flood control as well.

The two essential factors, water and fall, may be considered as mutually compensating in a large measure. If in one instance a small quantity of water falls from a great height it will yet be capable of generating considerable energy. Inversely at a lower height of fall a great volume of water can effect the same result. Thus there are two well defined types of power producing streams or power locations on the same stream, of high fall or "head", and small volume of water, of low fall and large volume of water. As a general rule, it is found that if the power generated in the two cases is the same, the cost of production will not be the same for the high fall can be developed and operated at a lower cost than the lower head, larger volume, plant. Head, therefore, has an advantage over volume of flow of water and in hydroelectric development generally the fall is the factor of more decisive importance than volume of water.

It is generally true that we find the large potential water powers in regions of high rainfall but estimates can only be regarded as satisfactory when a number of other factors have been taken into account. The most

reliable results in the estimates are gained when the actual stream flow of the rivers is taken over lengthy periods for obviously the amount of runoff varies with the amount of rainfall with the surface conditions of the watershed, especially the nature of the soil and its vegetation cover and with climatic effects, such as evaporation, frost or melting snow.

The value of the water powers of streams is greatest where there is least variation in flow. In regions of strongly marked wet and dry periods, while potential water power may be very great when the streams are running full, it may be practically non-existent in the dry season. For that reason many streams of Central and Southwest Africa, South America, India, Mexico and the southwestern United States are unfavorable to water power development until such time has arrived that on account of increased population in these regions intensive industrial development justify the building of reservoirs on a large scale basis similar to the development just completed on the Colorado River and the one under construction on the Columbia River in the western part of the United States. In periods of high water in the streams, however, many of these regions contain vast potential water powers. The case of the Congo Basin is often given as an example where about one-fourth of the world's potential water power is available, mostly about Stanley Falls and between Stanley Pool and the Atlantic Coast.

It is often pointed out that water power will develop principally in regions where it can successfully compete with fuel power. There is much truth in this statement, witness for example, water power development in Scandinavia, Iceland, Labrador, Canada, where in spite of hard climatic conditions water power has gained ground, often rapidly, as in those countries there is no coal. In California water power development went forward rapidly until the lower cost of development and power production based on local oil and natural gas resources curtailed water power development for the time being. When in the future fuel cost becomes higher water power development will, no doubt, be resumed.

Water powers, as we have seen, are to be found in larger amounts principally in once glaciated regions (Blanchard, 1924) where high falls, or a large head, is combined with a large volume of water at natural water falls, or at artificially created falls in large rivers, but also in localities where the fall is large and the volume of water is only moderate or small as is the case in the upper courses of mountain streams. In its middle or lower run the stream generally carries more water but the gradient is flatter and the amount of power that can be developed may be less than it was at the higher elevation. The cost of development is also higher in the middle or lower course of streams as large works are needed requiring not only a larger amount of material of construction but also more difficult foundations. In the higher regions transportation for construction is more difficult and costly.

Due to new types developed and improvement in design of hydraulic motors in recent years has the lower limit for practical utilization of water falls been considerably reduced. Water power development at many low

falls formerly not considered feasible have been undertaken, notable examples of which are the Vargön plant in the Göta River in Sweden, where the head on the plant is from 4.85 to 3.10 meters. The Lilla Edet plant in the same river operates under a similarly low head. The utilization of such low falls have only been made possible with the rapid development of a new hydraulic motor of unusual adaptability, the Kaplan turbine.

It is evident that geographical consideration in regard to amount and type of water power are of importance. The influence of geographical location upon the necessary constructional works for its utilization will be briefly considered in the following:

In earlier times of water power development only the impulse force of the flowing water was taken into consideration and utilized but with a more advanced technic the weight of water was also made use of with the overshot wheel and herewith the significance of fall, or head, of the water recognized as an all-important factor in the yield of water power.

The regions of the world best situated as to potential water power are the once glaciated parts of the world of mountainous character of the land furnishing the highest falls and so offer the best prospects for development. These are the regions of long chains of folded mountains in the old world and in the new. In the mountains of the Alps and of the Appalachians as well as in Scandinavia the first water power developments of recent types were established during the last century. Here along the larger streams in their lower reaches as well as at localities of hanging valleys, the industries of that period found a foothold. Transmission of power on a large scale was not yet developed and "factories made the ascent of the mountains". The heavily faulted regions where in relatively frequent change high and low fault blocks lie side by side as in parts of Europe, and in North America were also favorable regions for the development of water power. The table and plateau regions lying at high elevations and circumscribed with border faults, as for example, the borders of the meseta of the Iberian Peninsula or the Horst regions bordering the Rhine Valley, in the Harz and the Erzgebirge Mountains. The regions of glacial accidentation, where in relatively short time since the glacial epoch, the slopes and offsets in the valleys have not as yet had time to become eradicated, as in Scandinavia, in Finland and in the Great Lakes regions of North America, are found water powers of magnitude.

Where natural waterfalls exist, especially in the higher mountains, is often the constructional development, save for generally existing difficult transportation conditions, comparatively simple, in other cases, however, where the fall must be created through artificial means, such as tunnels, river cutoffs, river diversions, high dams, etc., in order to obtain a concentrated fall, does the construction of a water power development call for the highest technical skill. Examples, such as the Waeggital Dam in Switzerland, where the body of the storage dam was built previously to putting in its foundation, is one example, the final "holing through" of tunnels underneath mountain lakes, as at several developments in the Alps, in North America, another example. The Rodriguez storage dam in Mexico

had to be built in a location where for a distance of thirty meters there was no suitable geologic formation on which to build the structure. At the Copco Dam in northern California in the Klamath River in the porous lava formation the foundation had to be sunk thirty-eight meters below the river bed instead of an expected depth of seven or eight meters.

Erosional forces and sedimentation are of great importance and must be carefully considered when developing a storage dam site for power, public water supply or irrigation. The sediment transported under favorable conditions assumes stupendous volumes causing, when not carefully guarded against, large increased costs in the operation and maintenance of a water project. The erosion is especially dangerous on the downstream side of dams, undermining the structures, as has been the case with many dams in the United States, Granite Reef, Muscle Shoals, Coon Rapids, Calderwood, Austin, Natchez, are only a few examples where structures have been endangered or destroyed by erosion. Various types of protections have been developed in recent years, energy dissipators, such as baffle piers at Gatun and Pit 3, and the toothed types of "Zahnschwellen" by Rehbock. The slope of a mountain, the gradient of a stream, also have influence upon the velocity and coefficient of discharge of the precipitation thereby affecting erosion and sedimentation near the development of a water project.

When it is found desirable and feasible to install impounding reservoirs or storage works on a water course the orographic suitability of the region is of first importance as will be treated more fully in the next section Geology.

The amount of water power that can be utilized in a region depends also as we have seen upon the precipitation. Most favorably situated in this respect are of course those so situated that they receive an ample annual precipitation, so before all regions near the coast and mountains which receive a great part of precipitation brought in by moisture-laden winds to be delivered here in the form of rain or snow. Here again the combination water and fall must be on hand for else the precipitation in the greatest amount is of no avail. The precipitation needs to be uniformly distributed over the year in order to cause a uniform flow to furnish the industries and other power consumers a steady reliable power. Few large industries under modern conditions work decidedly seasonally, prime power is in demand during the entire year, secondary or seasonal power is generally of lesser value. Where long periods of dry weather and periods of heavy torrential precipitation succeed each other, as for instance in monsoonal regions as well as in other parts like the Great Basin, the Colorado Plateau, the Sierra de Córdoba, etc., development of prime water power without the resort to extensive storage works from which water can be released and the flow made uniform in volume is problematic or not economical.

But as a shortage of water is inconvenient or near-disastrous to a development, so are also great floods often a menace to the utilization of a water power. During high water periods the operation and production of power is made difficult or impossible due to rising backwater reducing the head on the plant when not actually flooding it or causing damage to structures

and machinery. The most recent example of this kind was the inundation of the large hydroelectric plant of the Louisville Gas and Electric Company at Louisville, Kentucky in the 1937 unprecedented flood of the Ohio River. This new plant designed with the data of the flood of 1884 available was thought to be comparatively safe against flooding but published photographs show the water to have reached a height in the power house to completely submerge the exciters on top of the vertical generators. This will no doubt mean a complete rehabilitation of the electrical installation of the generators at a large cost. In some cases in regions with frequent floods occurring special devices, fall-increasers, siphon effects, have been installed in order to decrease the height of backwater on the plant. Coosa River, Ala., plant is an example of this kind of device.

The influence of temperature upon the amount and value of a water power or water project is of no small concern, as it is capable of causing great variation in the flow of water in a stream. As soon as the temperature climbs to higher values so also is the amount of evaporation increased which again lessens the flow of the stream. High temperatures also reduce the flow to the stream through the increased consumption of moisture by the richer plant vegetation for the building up of organic substance. Where further by already low precipitation heavy evaporation takes place, water courses dry up entirely or furnish too little water for operation of the water power plant.

On the other hand, a high temperature might cause an increased flow of the stream insofar as it facilitates the melting of the stored snow and ice cover of the winter, thereby increasing the flow of the streams, sometimes even causing a distinct difference in amount of flow during day and night in similitude to glacial streams. Low temperatures cause non-uniform flow through the retention of the winter precipitation in the form of snow especially when a considerable part of the watershed is situated at high altitude as in the Alps, in Norway, in the Sierra Nevada of California. Ice covering on canals, forebays, and the freezing up of pipe lines and trash racks often cause considerable damage. Ice slush even in the largest canals and head races are an additional operating expense causing irregularity in operation necessitating closing of the plants, as is for example the case on the 30 kilometer open headrace canal on the American River plant in the Sierra Nevada at 1,200 to 1,500 meters elevation. On that account it has become modern practice in regions with long strong frost periods to place the water conduits and sometimes the entire water power plant underground, as for example at the Porjus plant in Lapland, the West Dalelv plant, and other plants in Sweden.

In forested regions, especially where deciduous trees abound, the leaves cause great inconvenience and expense to water power plant operations during the autumn as they float with the current of the stream or are propelled by the wind toward the intake works of the plant where they clog up the racks together with branches and other floatage. In modern plants where great difficulties in this regard have been experienced, mechanical rack-cleaning devices have been installed.

Temperature and atmospheric pressure have an influence upon the stability of the potential of a transmission line system. This is a distinct geographical location factor. In the Sierra Nevada in high altitude heavy snow is liable to cause destruction to conductors and insulators and short-circuits occur with loss of power or serious damage. Along the coast when the temperature drops low, the conductors become heavily ice covered up to 15 centimeters diameter or more before they break or tear down insulators and towers when a strong wind comes up.

In the higher regions it is often not the cost of the damage to transmission line systems that worries and irritates the power producers, it is the difficulty of access during the winter with its deep snow cover and cold that endangers the power service. In the Sierra Nevada regions men are stationed along water conduits and transmission lines all through the winter using snow shoes, skis and Alaskan dog teams, as means of transportation for reaching damaged or endangered locations day and night in shortest possible time.

The regulating effect that a storage reservoir or weir pondage offers to a water power development has already been mentioned. The physical requirements for the construction of effective reservoirs are many, they are of orographic, geologic, climatic nature and different locations are not equally favorable and consequently is also their influence upon the water discharge different at different locations. Similarly as these artificial regulators so act also natural regulators of the water discharge from a watershed, such as lakes, extensive swamp and marsh regions, large forested areas, lava fields, as well as snow and ice regions. These agencies all tend to detain the precipitation, delay the runoff in various degrees to be gradually released to a uniform-tending discharge. Above all are the mountain lakes and high moors contributors of a relatively large and steady unit time flow. Many such lakes have in recent years been developed into storage reservoirs by raising the threshold of the outlet by dams and successfully put to use in service of power production, so the Suorva Lakes in Lapland, northern Sweden, in Scotland, in Central Europe, in California. According to geographical location lakes have been raised or lowered in level or their waters diverted to more favorable locations to serve power purposes as seen in such examples as the above-mentioned Suorva Lakes at the Porjus plant, the Walchensee in Germany, the Ritom and other lakes in Switzerland, the Lake Fordyce, Lake Spaulding, Copco Lake, Florence Lake, Huntington Lake, Echo Lake, Medley and other lakes in California. Through the existence of lakes, moors and marshes the low water flow of the streams is also enhanced as all of these retainers are more or less fissured or porous, releasing some water through their bottom layers as seepage.

Snow and ice cover within a watershed especially when located at a high elevation have a decided influence upon the regimen of a stream. The melting-waters therefrom cause the stream to hold up its low flow in the warmer season when the runoff from the watershed else is small and the evaporation high. When a stream originating in a snow and ice

region lower down in its course runs through a forested region of watershed these two portions of watershed tend to stabilize the flow throughout the lower reaches of the stream. The streams of the Pacific slope with few exceptions do not have this characteristic for although they are fed from residual snow in many cases during the summer their middle reaches are entirely rainless for many months and as far as the Sierra Nevada streams are concerned their lower courses are very short for all except the two longitudinal valley streams.

The economic factor has as great weight in the geographical distribution of hydroelectric industry as the physical factor. The first problem encountered in the construction operations when about to undertake an extensive water power development or other water project is that of means of access. In this respect almost every kind of means of transportation to the site has been used. In California standard equipment railways, inclined tramways, hairpin-turn trucking roads, of great length and steep gradient have been used. In Sweden standard railway tracks built over the ice-covered lakes in far north above the Arctic Circle and airplane service, in Switzerland and in Norway aerial tramways of considerable length and capacity came into use, in the Malay Peninsula and New Guinea again airplanes hauling all heavy machinery and equipment to the site of development. Skilled mechanics for the installation of mechanical and electrical equipment must be brought from the larger centers of industry and common labor is sometimes scarce in number at the site and when there found not of extravagant efficiency.

Some sites are shut off from all communication for a long time of the year. At storage works in the High Sierra of California for example, only about three months of the year are open for construction work, the same condition prevails in the Alps, in Scandinavia, in Canada. Entire dam or power house locations have been housed over and heated in order that work might be carried on during the cold season but the cost of construction under such conditions of course runs high and not often practiced. Recreation facilities for workmen and staff must be provided in out of the way locations in the form of libraries, billiard halls, cinema, even tennis and golf courses have been built — the psychological factor cannot be ignored — the effect of living in a remote place in regions of wild and hostile nature.

The significance of transmission of electrical energy and its attending problems have already been touched upon. Few large hydroelectric developments find a market for the power they produce at the site, principal exceptions are in the mining and the pulp and paper industries, else the power is transported by means of high tension transmission lines to near the point or points of use. Transmission at generating voltage is not economical, the voltage must be raised through transformers then transmitted or transported and the voltage lowered to tension values suitable for distribution. The attendant costs are economic factors to be considered when development of a water power is under consideration.

In recent years great progress has been made in pooled or unified electri-

cal operation by which is generally understood the working together of several plants of different ownership or systems with different climatical and hydrographical characteristics and serving a common transmission net which takes care of the load peaks and minimizes the climatic catastrophic danger of the single plant through the equalizing effect of the whole unified system. Geographically this means the transmission of a favorable climatic effect from one location to another location where at the moment it is needed to replace or to counteract less favorable local climatic effects.

An intensive water power utilization requires the widest possible control of the flow of the stream developed in order to obtain best economic results. When using only a part of the flow and no pondage the development is least feasible from the view of water economics. Better results are obtained when making use of a small weir and pondage capable of furnishing a steady flow to the plant during the day or week as the case may require. Further than this, the regulation is favorably effected by the use of a storage dam or reservoir of considerable size permitting storage of seasonal or total yearly flow from the watershed. Of especial interest geographically are instances where the major part of a water course is diverted into a canal, flume or tunnel to a power plant farther down on the same river around a curve or bend or in extreme cases into another watershed where a larger head can be made available for power development. In the last case the stream channel will be laid dry permanently or will serve only to carry off floods occurring on the watershed that cannot be stored in the reservoir above the diversion to the power plant. In a stream whose hydraulic regimen has been in this way changed vegetation and animal life will also change in varying degrees depending upon the degree of change in the water conditions brought about. Various types of diversions of tributary rivers through canals, pipe lines, siphons, flumes and tunnels are standard practice in water power engineering. Lakes are raised, lowered, tapped and diverted to where the greatest fall for water power development is obtained.

When the natural flow conditions of a stream are disturbed by works of man the natural discharge conditions are changed and the phenomena of erosion, sediment transport, and silting, come into play as reactions to the disturbance. This action of erosion, sediment transport, and silting are due to the force of flowing water and obeying the laws of physics. The utilization of the water power is the extraction of energy from the stream at a location where volume of water and height of fall can be most conveniently concentrated and there converted into mechanical energy through a hydraulic motor. At all other locations along the development the water is deprived the opportunity of giving off energy and diminution of volume of water and of height of fall is sought to be kept at a minimum. The whole utilization of the water power consists chiefly in depriving the stream of its energy. Where the flow of water is too great erosion will take place, the material to be transported by the stream where the velocity is sufficiently high, and it will be dropped by the stream when the velocity is too low for keeping it in motion.

Sudden changes of volume and direction of flow are factors that cause the above phenomena of erosion sediment transport and silting. They are of utmost importance to know about and must be carefully guarded against especially at intake structures to canals and tunnels, at curvatures in alignment, at high velocity spillways, at the lower side of overflow dams, in turbine chambers and in draft tubes. Conservatively selected velocities, protective works and energy dissipators, well-built foundations, are most important features required in hydraulic construction works.

In a region where water power development is undertaken the geographical factor of landscape view is affected favorably or unfavorably to a lesser or greater extent. The structures erected for the utilization of a water power such as dams and regulating works, intake towers, spillways, canals, siphons, pipe lines, surge tanks, penstocks, power houses, afterbay regulators, all have an influence favorable or unfavorable upon the view of their surroundings of which they are made a part, or ought to be, at least. A reservoir lake in an arid region creates a great attraction as indicate several instances in the south-western United States, a large storage dam structure is an imposing sight in any river canyon, as for example, the Arrowrock Dam, Boulder Dam, Owyhee Dam, or in a landscape of milder relief energy as the Vyrnvy Dam, Chemnitz Dams, Gileppe Dam and many others and in this respect we frankly disagree with (Fels, 1935) where he praises the beautifying effect of the storage reservoirs but feels disappointed with the "hässlichen Mauern der Talsperren". And Europe has less reason for complaint in this respect than have the Americans where first very recently engineering structures have received an architectural treatment.

A striking feature of many Sierra Nevada landscape view are the winding canals and flumes along many seemingly inaccessible locations on the hillsides and precipitous canyon walls such as seen on the South Fork of the American River, on Mokelumne, Stanislaus and other rivers. Steel and concrete siphons descend the hillsides to cross a valley and water course to rise on the other side again to the same height continuing on this side of the valley, crossing the valley or canyon on a large bridge structure of steel, or concrete, or disappear into a mountain in the form of a tunnel; surge tanks, seemingly glued to the mountain sides just before entering steel penstocks, that singly or several continue to the power plant. The power house structures, often most imposing as Rjukan, Trollhättan, Pit River 1 and 3, Big Creek, enhance the landscape favorably. Generally the hydraulic construction features improve the view of the landscape in which they are set more than do the quite often unsightly looking steelframe transformer yards, switch yards, transmission towers, substations. At or near the larger water power developments the small communities populated by the attendants of the plants often form a favorable feature of the landscape view, especially when some attention is given to the architecture of buildings and to gardening. Formerly the plainest board cabins were good enough, often unpainted, whereas nowadays schools, cinemas, community centers are important features of the view of landscape of the larger hydroelectric developments.

When the natural regimen of a stream is disturbed through a water power development or water project the landscape will in a lesser or greater degree take on another aspect. The river is laid dry permanently or temporarily through a longer or shorter period of the year and this has a reshaping effect upon the landscape at least along the banks of the stream where the vegetation will change in character and abundance. But not only can the flow be smaller than pre-development low flow, it can also through regulation be made permanently higher than the average before development took place. These changes, while apparently small, are of a permanent nature and will cause greater changes along a stream than the just periodical short duration variations due to its natural high and low stages.

When storage reservoirs are drawn down seasonally they generally create an unattractive scenic feature, especially where such reservoirs have been created and filled to their high water level without clearing the shores to be inundated but forests left standing to decay in water. Of recent years it has become practice to clear reservoir sites of trees to above high water line. Under circumstances when reservoir lakes are drawn, especially low mud flats and sand banks become exposed for longer or shorter periods of the year (Fels, 1935). The influence upon the view of the landscape is then an unfavorable one.

To what extent the creation of storage reservoirs and artificial lakes have an influence upon the climate of their locality is a mooted question, much discussed. That the largest reservoirs reduce the daily and annual temperature extremes in their immediate vicinity a phenomena laid to the heat radiation and evaporation of the water, although in very small amounts, has been claimed established. Careful observations and comparison of records at the Salton Sea in California created through the inbreak of the Colorado River into the Colorado Desert in the years 1905—1907 show that the formation of the lake has had no perceptible effect upon local precipitation. Considerable discussion had arisen as to whether the formation of the large artificial Lake Mead at the Boulder Dam in a region previously without large masses of water might not cause marked effect on local weather conditions. The question arose principally as the result of statements made by airline pilots that they had noticed a marked effect, a drop in temperature at considerable elevations above the lake. However, both the United States Weather Bureau and the U. S. Geological Survey are of the opinion that while unquestionably a large amount of evaporation will take place from the new lake the effect of this upon local rainfall will be imperceptible. Local evaporation is only a minor factor, they contend, in local rainfall which is determined by the large-scale distribution of atmospheric current, the distribution of mountain ranges and similar factors. Local evaporation is quickly scattered over a wide area and it is unlikely they state, that the Lake Mead section will notice any increase in local precipitation. Moreover, if any conclusive results were to be obtained it would be necessary to check long-term periods rather than individual years and to compare those records with test areas removed from the Lake Mead influence yet having comparable climate. For these reasons the Weather

Bureau which has a number of observation stations in the surrounding territory did not consider that any extra stations were necessary.

From the viewpoint of economic geography there are numerous factors of influence of geographical conditions upon water power and their utilization that are of importance. Marketing possibilities and transportation conditions, for example, have a great influence upon its value. The development of the finest water power is of no avail when no possibility exists for evaluating the power generated, transmission systems of great length may make its development cost prohibitive and the transportation of raw material for prospective industries at the water power site may also be higher than their competitive market can bear.

The utilization of California streams for water power purposes must take into account the water requirements for irrigation. The laws of California give the irrigator preference over the power producer in the rights to water. In many cases the same stream that furnishes power is used for irrigation after it reaches the foothill country. Practically all the important rivers that descend each slope of the Sierra Nevada are thus used. About the apparent conflict between the two uses of water mention has been made. Power demands a fairly uniform flow throughout the year perhaps an increase for irrigation pumping in the summer months. Irrigation demand varies between wide limits ranging from 1 or 2 per cent in some months to as much as 20 or 22 per cent of the total seasonal quantity used in other months. During two or three months of the year there is no irrigation and then the reservoir gates are closed to store water for the next year.

The solution of this problem must be found in the difference in reservoir location. Power requires that water be stored near the head waters of the rivers in order to take advantage of as much fall as possible. For irrigation, however, the reservoirs are needed near the exit of the river from the mountain in order to obtain the greatest tributary watershed. Whatever water is released from power storage reservoirs during the irrigating season is of benefit to irrigation passing directly to the lands. Water released for power during the non-irrigating season can be retained in the irrigation reservoir for use the next season and thus insures against a failure of irrigation water for a possible future deficient flow of the stream. The irrigation reservoir becomes in effect a re-regulating reservoir changing the stream from the character given it by power regulation to one serving irrigation.

An excellent example of the far-seeing attitude that California power producers are adopting in cooperative development of storage for power and irrigation purposes, the case of the Melones Project on the Stanislaus River might be cited. It is further as nearly an approach to the acquisition of a dam and regulated supply of irrigation water at no cost to the irrigator as has yet been reached in California for the revenue from power will very nearly pay not only the interest but the redemption of the bonds. Here the Melones Dam and Reservoir impounding 138,771,000 cubic meters was constructed by the irrigators of two irrigation districts with over 50,000 hectares of good irrigable land. The irrigators were also obliged to acquire

all necessary rights, easements and permits necessary for a 30,000 kw hydroelectric plant and turn these over to the power producers. Between March 1 and October 31 the irrigators control the release of water.

The power producers obligations were to construct the hydroelectric power plant. To control the water from October 31 to March 1 but between December 1 and March 1 to release 44,406,720 cubic meters for the purpose of filling an existing reservoir lower down the river. To pay \$ 5,175,000 to the irrigators in forty years in semi-annual installments of \$ 64,687.50.

On the Merced River the Exchequer Dam has been built to store 356,478,280 cubic meters by the Merced Irrigation District. In this case the irrigators themselves built a power plant of 25,000 kw capacity at the toe of the dam, the power produced being sold wholesale at the switchboard to a large power producer, the plant to be operated to suit the irrigators requirements. The life of the contract is twenty years renewable at the irrigators' option for twenty years more.

In the Don Pedro Dam and Reservoir on the Tuolumne River the Turlock and Modesto Irrigation District has a similar project in operation with a storage capacity of 351,553,200 cubic meters and a 30,000 kw hydroelectric installation and farther down the same river the La Grange hydroelectric plant of 4,300 kw capacity.

In a similar way have the public water supply systems of the larger cities in California arranged for production of hydroelectric power in connection with their gravity actuated conveying water systems from high altitude watershed to the distributing reservoirs near the points of use.

The City of San Francisco has developed the Hetch Hetchy water supply system. From a rugged granite watershed of 170,000 hektares of uninhabited lands rising to an elevation of 4,000 meters the waters from the melting snows and glaciers are impounded in two reservoirs Hetch Hetchy and Lake Eleanor at an elevation of 1,160 meters. The Hetch Hetchy Reservoir through the O'Shaughnessy Dam, the greatest total height dam in California, impounds 444,667,720 cubic meters. In the conduit leaving the reservoir one power drop of 400 meters static head has been developed, the Moccasin hydroelectric plant with an 80,000 kw installation capable of being increased to 120,000 kw. The Moccasin power plant is a very attractive structure in Mission style. The city's income from the wholesale of power amounted to \$ 2,000,000 annually in recent years.

The East Bay Cities comprising Oakland, Alameda, Berkeley, Richmond and a number of smaller communities formed the East Bay Utilities District in May, 1923. The Lancha Plana damsite on the Mokelumne River was selected for development and the Pardee Dam and Reservoir was built. A power plant of 20,000 horse power capacity was built at the toe of the dam the annual amount of power generated varies from 75 to 125 million kwh a large percentage of which is primary power.

The City of Los Angeles is also producing hydroelectric power in connection with its public water supply system. The Los Angeles Aqueduct, a notable undertaking, which conveys a large supply from the Owens River to Los Angeles 360 kilometers away, was completed in November 1913.

Several power sites are utilized, both in the Sierra Nevada tributary to the intake reservoir of the aqueduct as well as along the aqueduct proper between the intake reservoir and Los Angeles. On the southern slope of the Coast Range are located the largest of the hydroelectric plants on the route the San Francisquito No. 1 of 65,000 kw and the San Francisquito No. 2 of 42,500 kw as well as the San Fernando of 6,400 kw capacity. Total output capability of 12 hydroelectric plants in connection with the aqueduct system is 138,000 kw and the total output when full development has taken place, will be 162,500 kw with an installed capacity of 244,860 kw.

From the foregoing brief discussion of geography as related to problems concerning water resources, their collection, conservation and utilization for public water supply, irrigation and water power, it is evident that many important such relations exist. The geographical location, the surface forms and configuration of a region are important. The conditions of precipitation as regards quantity, time of occurrence, duration, its form, whether as rain or as snow, factors of climate, natural and artificial regulating factors, and last but not least, the location with respect to transportation facilities and other economic geographical factors, all of these have a bearing upon the feasibility of a project, upon its successful planning, construction and operation. It has also been touched upon briefly the influence a developed project with its accompanying changes in water regimen, with its creation of new water bodies and reservoir surfaces has upon the water course and adjacent lands, further, the favorable or unfavorable effect upon the landscape by buildings and structures erected and now made a part thereof. Examples where such buildings have enhanced their surroundings and the landscape are many, the number of eyesores where a before beautiful scenery has been totally spoiled through the erection of ill-fitting structures of ill-suited materials are very numerous.

II. Geology.

Although geology has existed for more than one hundred years it was still at the beginning of the twentieth century looked upon as a pure science without application to technical works of man and without a part in the great progress of commercial development or in the development of the water resources for public water supply, irrigation and water power. There was a foundation to be laid and much to be done in correlating and following up the extent of rock formations in which the study of fossils had a large part. As this phase of the science seemed mystical and a waste of time and funds the geologist came to be known as a fossil hunter whose interest seemed to be apart from the welfare of his fellow men. The layman knew little about what geology possessed to help him and the geologist was too much out of contact with the problems of a budding technical science to make its problems a part of his own.

In earlier times it had generally fallen upon the mining engineer to solve the problems of practical geology and he was also the constructor and builder of hydraulic works. In the days before railroads and large-scale

inland navigation requiring tunnels, heavy foundations for bridges, locks and harbor walls, the largest constructional undertakings were in connection with mining, in the building of shafts and water tunnels accompanied by hydraulic works for water power and mine pumping. The scientifically trained mining man was admirably equipped for this work and became the professional expert in the applied science of geology. When taking notice of the tremendous water collecting and mine drainage facilities of the larger developments in the middle ages, and later, such as found in the Harz Mountains in Germany (Brüning, 1928), in the deep copper mines at Falun and the equally deep silver mines at Sala, Sweden, and at numerous other locations in Central and Northern Europe, one is astonished at the works successfully carried out. The work of driving a water tunnel took forty years where today the compressed air drill and high powered explosives pierce through in as many days, and hauling equipment was primitive.

With the times, however, things have changed. Progress in geology has been rapid and the usefulness of economic geology has come to be recognized. The office of State Geologist of California to which the eminent scientist J. D. Whitney was appointed in 1860 was abandoned a few years later by the Legislature because he undertook more fossil hunting than suited the people and the law makers of the State. The position was re-established in 1874. The teaching of the elements of geology is today prescribed by the best technical colleges and universities, costly mistakes and misjudgment of rock and foundation conditions on some large construction projects have stimulated interest in the contribution which geology has to offer and many eminent geologists have come to specialize in economic geology in connection with large projects of engineering construction, such as tunnels, foundations, reservoir sites, dam sites, canals, water power and harbor development. As projects grow in magnitude with the necessity for opening up larger tracts of the bowels of the earth, the driving of larger-bore, longer and deeper tunnels, the creating of tremendous artificial lakes, such as Gatun Lake, Lake Mead above Boulder Dam, the Lake of the Ozarks, to mention only a few, through damming of water courses with the modern day highly specialized dam structures and for many other similar purposes, the rocks, their stability and permanency need to be carefully studied and this has come to be an important branch of economic geology.

The need for more thorough geological investigations and study in connection with engineering projects became more pressing with the modern undertunneling of rivers flowing through large cities, as the Thames, the Seine, the Hudson, the Spree. Water supplies for cities was another undertaking requiring knowledge of the rocks and structures involved, such as the collecting works at Wiesbaden, groundwater at Paris and Berlin or tunnel works, such as New York, Boston, Chicago, Liverpool, London. With the building of large storage dams another most important field was opened up requiring the attention of the scientifically trained geologist.

In works on hydraulic design and construction published before 1900 little attention is given to geology. True, they point out, the importance

of a good foundation and water-tightness where required, leaving it to the civil engineer to find out as best he can about properties of rocks and of structures which he might encounter. In Europe the dam builder Intze and later Mattern and Ziegler, Sympher and the geologist Leppla, in their works dealt with the importance of geology in connection with large dams. Already in 1853 the French engineer M. de Sazilly had published his profile of equal resistance making less extravagant and more economical designs possible than had been employed in the old Spanish dams and a rational theory regarding the proper methods of designing a masonry dam was herewith in the making, a technical scientific task not yet completed. Herewith arose also the necessity of knowing the strength and structure of the rocks on which large dams were to be erected in order to fully utilize the new knowledge when applied to practical construction. The origin, occurrence, character and composition of the various rocks, the structure of the formation and the location of any existing faults and the dip of the strata, all these features it became necessary to investigate and the geologists report and the geological map by the professional came to be a matter of course required in connection with the construction of large dams and reservoir development for water power, public water supplies and irrigation projects.

All structures built by man constitute a load on the crust of the earth. If this crust were everywhere uniform and of the same character and strength the design of structures could be much simplified but the heterogeneity of the materials of the earth's crust and the complexity of their arrangement are "notorious" (Bryan, 1929) and these geologic conditions enter into most engineering problems. Selecting reservoir sites whose natural walls offer no chance for excess leakage, choosing the proper environment for the construction of dams, ascertaining the character of the rock, its structure and the possibilities of menace from ground water in driving tunnels, analysis of currents, wave action and undertow, in harbor improvement, investigation of stream scour and the character of rock foundation for large bridge piers and abutments, study of the causes and means of prevention of landslides, contributing information with regard to sources of underground water supplies and their control, diagnosis of the geologic factors affecting problems of water supply and drainage and a great number of other problems incidental to the work of the hydraulic engineer are some of the problems in which geology may contribute to the success of engineering projects.

Location of reservoirs has of recent years become a most important professional service furnished by the experienced geologist generally operating with or in advisory capacity to the hydraulic engineer. From a geological standpoint the main consideration in selecting a reservoir site is that the rocks be water-tight. The formation underlying the reservoir should be as nearly impervious and insoluble as possible, free from any faulting along which leakage might develop and should contain no underground cavities. For example, the porous lavas such as encountered in the region of the lava-covered plateau north-east of Mount Lassen in Cali-

fornia, formations containing layers of gypsum and limestone in which underground cavities may exist, are often unsuitable reservoir sites.

When a reservoir is filled water escapes from the basin to the ground adjacent. Not only do unlined reservoirs leak appreciably but even concrete and brick lined reservoirs leak to a certain extent and in consequence of these leaks the foundations of a few reservoirs have been undermined with disastrous result. Large reservoirs are of course not lined as the cost is prohibitive. For that reason unless the leakage to the ground is resisted by natural conditions or is small and inconsequential the reservoir is a failure. As leakage must be resisted by the characteristics of the ground sufficient "piping" or "creep" distance must be developed and study of a reservoir site is a geologic groundwater problem.

Ordinarily the soils and rocks are saturated with water below a certain depth the top of this saturated zone is the water table. It lies deep beneath hills and comes to the surface at marshes, in valleys and at streams. In valleys it slopes downstream from both sides toward the middle and so it generally takes the shape of the surface topography. Such a form is due to the resistance to flow afforded by friction in the interstices of the ground. The gradient of the water table at any place is a function of the size and number of the interstices or pores in the ground and the quantity of water. A steep water table thus indicates tight ground of small porosity or very large quantities of water conversely a flat water table indicates larger pores or openings in the rocks or very small quantity of water.

In the construction of dams across valleys water from the resulting reservoir will sink into the ground until it meets the enclosing water table and the latter will take a new grade. If the surface of the reservoir is below the groundwater divide not only will there be no loss by seepage from the reservoir but there will be an inflow of groundwater into the reservoir and an underground storage between the old position and the new position of the water table. In general when the reservoir is built in a valley whose stream is fed by groundwater, little difficulty is met with although it is possible that leakage overtops the groundwater divide but the seepage will be moderate if the material of the divide has a low porosity. Where the enclosing walls of the reservoir are wholly or in part of open-textured material, such as basalt, scoriaceous lava, cavernous limestone or an accumulation of glacial boulders and coarse gravel, the groundwater divide is generally also low and with it also the position of the water table low and large leakage will result. Leakage through gypsum or rock salt and to a lesser extent through limestone formation will increase as the rock is dissolved and fissures enlarged but leakage through basalt will as a rule remain constant or slightly increase (Bryan, 1929).

Leakage through boulders or gravelly material may increase by the washing away of the finer material from the pores induce settling and landslides of serious consequence. When the openings through which leakage occurs are small they may gradually decrease by reason of deposition in them of sediment carried along by the water. Silt carried by the water may cause a leaky reservoir to become tight after shorter or longer

time of use. In India the Muchkundi Tank formed by a masonry dam on schist formation was sealed and made tight after 12 years of silting. In Yorkshire, England, a reservoir formed by a dam 25 meters high, leaked 1665 cubic meters daily through fissures in the rock foundation. After two years of use the fissures were sealed by the deposit of silt and leakage ceased. In California the Chenery Reservoir located on a sedimentary formation of clay and adobe was sealed with bentonite—a claylike material containing 75 per cent or more of beidellite formed by the devitrification and partial chemical decomposition of a glassy volcanic ash. The result of this bentonite treatment was a reduction in leakage of about 60 per cent the area of the reservoir being 87 hectares with a depth of 8.50 meters.

Twenty-five years ago the City of Seattle, Washington selected a reservoir site on Cedar Creek, a tributary of the Snoqualmie River on the west flanks of the Cascade Mountains. At a point of a canyon-like constriction, rock-walled and rock-floored, above which the valley widened affording what appeared to be a capacious reservoir. A dam of first class concrete construction was built at the valley constriction and upon completion and the closing of the gates it was found that the impounded waters were finding their way through one of the natural walls of the reservoir, due to the high porosity of the glacial materials of which the valley was made, a condition that was previously warned about and condemned by a competent geologist. Some leakage through the seamy rock of the south abutment took place but large and disastrous leakage occurred through the glacial material that formed the ridge between the two rivers. It is stated that when the water in the reservoir stood at an altitude of 474 meters large springs broke out in the Snoqualmie Valley at an altitude of 301 meters. The hydrostatic head was 173 meters and the distance 2,000 meters, making a gradient of 1:11.5 (Fowler, 1915). The emergence of this leakage in Snoqualmie Valley caused sliding of the hillside. The total loss of water was 113,560 cubic meters daily or 1,315 cubic meters per second and in spite of efforts to stop the leakage the city was forced to choose a new reservoir site capable of meeting its growing needs and virtually abandon their old project which had cost them hundreds of thousands of dollars.

The Nogal Reservoir near Carrizozo, New Mexico was constructed about 1900 in connection with the Bonita River water system to supply a railroad with mountain water. The reservoir lies near the crest of a ridge in a zone of considerable faulting into which a number of dikes have been intruded. A large amount of leakage varying with the head to nearly 3,800 cubic meters daily, has always occurred along the faults. The largest leak occurs where the main fault crosses a canyon about 400 meters north of the reservoir. An effort was made to stop the leakage by cement injection but without result. A total of 203 holes was drilled to depths varying from 21.50 to 42 meters and 150 tons of cement were used in the grouting.

At the Santa Maria Reservoir in Colorado, leakage takes place through more than 3 kilometers of landslide material at the south end of the water body. At Mosco Reservoir in the same State leakage through shattered volcanic rock and morainal material has occurred. In the morainal rock

the water passed through 450 meters of sand and gravel and produced a washout leaving a ravine six meters deep.

Underneath large areas where the rocks are porous to cavernous, the water table lies deep. Water flows freely on low gradients in comparison to those of surface streams. Where the rocks are tighter the water table lies higher and only small areas may have a deep water table. The losses from a reservoir where the water table lies low are proportionate to the hydraulic head and the capacity of the rock to transmit water. In one locality part of the bed of a proposed reservoir in extrusive basalt was annually flooded by farmers with water from the spring runoff from local creeks. Water 4.50 meters deep disappeared in six weeks and as the proposed dam was to be built for 18 meters water depth it seemed likely that the whole water volume of the reservoir might be lost in a few months. Part of the floor was covered with fine-grained soil which retarded leakage but undoubtedly the velocities due to an 18 meters head would have carried down this fine soil into the basalt with following increase in the rate of leakage. The project was abandoned.

The Malad Reservoir near Malad, Idaho was designed for a height of 21 meters a length of 135 meters and was under construction in 1917-18 but stopped when the dam reached a height of 15 meters due to excessive leakage observed at that time and has never been finished. The geologist who reported on the failure says — "When the gates of this dam were closed and the reservoir filled to the 3-meter contour the water level rose no higher on account of the leakage. Even with a continuous flow of 0.70 cubic meters per second the entire flow disappeared into a talus slope on the south side of the reservoir about 360 meters north of the dam. Doubtless if the reservoir could have been filled to higher levels the rate of leakage would have been higher.

Shafts were sunk and extensive studies were made of underground water conditions in the reservoir. The water table map indicated that practically the entire underground flow sank in the locality of the talus slope mentioned and then disappeared in the limestone underneath within an area encircled by the 18-meters groundwater contour. The probable cause is a bed of soluble limestone in which water escapes along bedding planes widened by solution. The maximum area of leakage is probably not more than 150 meters long and 7-8 meters wide and probably the area in which the larger amount of leakage takes place is even smaller.

The Jerome Reservoir in Idaho is situated in a depression underlain by hundreds of meters of basalt flows. The water is far below the surface and leakage through the basalt though the rock was protected by a cover of soil 3 meters thick in places, was so great as to cause the abandonment of the reservoir. The Hondo Reservoir in south-western New Mexico is situated in a natural depression surrounded by fairly substantial limestone. Below the surface soil the floor is underlain by shale and gypsum as shown by drill holes and according to best information (Bryan, 1929) the water table lies about 60 meters below it. After the reservoir was constructed leakage

through the cavernous rock beneath it was so rapid as to cause the formation of sink holes in the soil and the reservoir was abandoned.

The Deer Flat Reservoir in Idaho is formed by two embankments that close a gap in the encircling hills. These embankments are not absolutely watertight and allow some seepage at the base. When first filled the reservoir had a relatively large loss of water from the floor and sides but the loss gradually diminished. The underlying materials consist of horizontal soft sedimentary beds mostly clay tuff and sand. A few basalt flows are interbedded with the materials and on the surface of the plain are discontinuous deposits of gravel. Before the reservoir was built the water table rose under this plain above the level of the adjacent rivers. The losses of the early years of the reservoir went largely into saturating the underlying beds and raising the water table. The irrigation of surrounding land was begun at the same time and assisted in this process so that the reservoir rests on saturated ground to which it loses only enough water to replace that drawn off by lateral movement to swampy places on the hillsides or to the rivers. No doubt silting of the bottom of the reservoir has also helped to prevent losses. It is evident that if the underlying materials were more permeable it would require more water to replace that lost by lateral flow.

In the State of Colorado along the South Platte River several storage reservoirs have been erected in natural depressions among sand dunes adjacent to the river. Seepage losses have been large but the losses decrease with length of use of the reservoir. This fact indicates that the seepage has built up the zone of saturation in the ground to a higher level and thus reduced the slope of the new water table and consequently lessened the movement of water through the ground. Deposit of silt undoubtedly has also tended to seal the bottoms and thus aided in lessening the seepage.

A peculiar condition exists in some localities, the perched water table, as described by (Bryan, 1929). This condition has been observed in New Mexico. In general areas of high water table are characterized by many streams flowing perennially and areas of low water table have few streams on the surface. In the investigation for the No. 3 Reservoir of the Carlsbad irrigation project in New Mexico Pecos River at the dam site is perched above a low-lying water table. The test well at this point encountered water between 7 and 13 meters which stood at 7 meters below the surface and 3.50 meters below the level of the river. Below this wet zone the cavernous rocks were dry to a depth of 22 meters and is probably the main zone of saturation of the region. Rio Pecos in part of its course through New Mexico and western Texas runs above dry rock in a kind of flume which it is believed was formed by the deposition of calcium carbonate from the water of the river in the gravel and cave breccia beneath its bed. The condition here described does probably not exist on the lower Pecos before its confluence with the Rio Grande. The present writer has carefully gone over that part of the river in search of damsites and noticed that many large springs are flowing near and in the river which would hardly be the case if the river was perched in a more or less water-tight flume.

In some instances where the leakage takes place over small areas earth dikes may be built to isolate the areas. At the McMillan Reservoir in New Mexico such a dike failed to stop leakage having no bottom cutoff and also because openings in the gypsum enlarged and carried off just as much water as before the dike was built. Other similar attempts have proved of doubtful value. Where the channels of water escapes are large and definite they can be plugged but only where the head or pressure is low. Grouting with concrete or asphalt have proved most successful, also clay. Stratified sands and gravels of glacial deposit do not make a good foundation for a reservoir unless the water-tight bottom for these materials are generally very porous. On the Devils River in Texas an extensive clay-blanket failed to completely stop leakage through, or possibly underneath it, from a storage dam of 12 meters in height.

Damsites of perfection from an engineering as well as from a geological standpoint are the exception rather than the rule. Streams follow lines of rock weakness in cutting out their canyons. These weaknesses are generally found along faults whose movements have shattered the rock and made it less resistant to the wear of water along contact planes between two different types and possibly ages of rock one of which is more resistant to water wear than the other or which contact may have been weakened by subsequent crustal movement and in regions where intensive distortion or folding of bedded formations has taken place. Purely erosional canyons through unweakened homogenous rock are rare although they occur and have been utilized advantageously for dam purposes. In reality however, the great majority of dam structures which have stood for many years span canyons which present some geological weakness. This because in spite of the geological weakness the rock is far stronger and more massive than the dam structure, than is necessary to withstand the pressures and stresses imposed. This is for example the case with some dams in the lava-covered country of the Columbia plateau and in northern California.

Weaknesses brought about originally by old movements of the crust of the earth do not necessarily prohibit the successful use of a damsite for dam purposes. In the older rock formations dead faults and intensive jointing are not necessarily to be feared as cementing materials have usually been deposited in the rock openings or such openings have been closed by mechanical processes during subsequent ages effectively closing them and restoring the strength of the whole or else reducing the size of opening so that grouting or other protective measures will accomplish the same result.

The preliminary location of damsites are generally made by engineers who survey and map water courses along stretches under consideration for dam and reservoir development in connection with public water supplies, irrigation or water power. After having mapped the river or reservoir sites and found topographically suitable sites the geologist is called upon to make a geological investigation and report. The study of damsites excites the interest of the geologist because of the necessity for precise and detailed work, like mapping in the Gastern Valley in Switzerland for the relocation of the Loetschberg tunnel to scale of 1:1000 (Buxtorf, Lecture). Funds

are also generally available for exploration work through test pits, tunnel drifts and core drilling to gain information not obtainable by surface examination. In determining the suitability of a dam location there are several geological factors which are of prime importance, the depth of the alluvial or other overburden which must be removed the strength of the foundation rocks to withstand the weight of the dam and the pressure of the water behind the dam, the permeability of the foundation rocks since the dam must be water-tight and the existence of any faults on which a movement might injure the dam structure.

The depth of the stream alluvium and other overburden is determined by shaft sinking or by drilling. The thickness of the alluvial deposit is governed by the topography and geologic history of the region, especially during the Quaternary period. By considering the geologic record the experienced geologist can often estimate the thickness of the overburden more accurately than can the engineer and determine from a preliminary examination whether or not the project is feasible from this standpoint.

A damsite is usually a narrow canyon or a valley constriction above which the stream flows through an enlarged basin. The existence of a steep-walled narrow canyon generally indicates that the rock of the canyon is harder than the rock in the upstream valley. This indication and the fact that canyons are geologically youthful features determine the favorable condition that the rocks in canyon walls are as a rule exposed and relatively fresh, particularly near and under the stream.

It is advisable, however, to determine why a stream as is frequently the case, leaves a seemingly easier course and turns aside to cut a canyon through hard rock (Ransome, 1928). A fault or other particular line of weakness along the canyon and concealed by gravel and boulders of the present stream bed is to be looked for. The presence or absence of a fault along the bottom of the canyon can often be determined by examining spurs and ridges that extend across the prolongation of the river axis at the damsite. In this way Ransome found a fault at the Owyhee damsite in eastern Oregon. The drill records suggested the presence of a fault under the river. Examination of the ground showed a little ravine and saddle in line with the gorge and a trench was dug across the ravine with a view to expose the fault zone. The fault was found as expected and provisions to deal with it were embodied in the design of this 123.50 meters maximum height dam built by the United States Reclamation Service.

At the location of the O'Shaughnessy Dam on the Tuolumne River at the lower end of the Hetch Hetchy Valley in Tuolumne County, California, the depth of the stream gravels overlying the granite bedrock was found to be excessive, the maximum depth being 31 meters. Owing to this condition a greater amount of excavation and a higher dam were required than originally planned which added greatly to the cost of the project (Clark, 1933).

When considering the strength and permeability of foundation rocks it is important to ascertain the origin of the rock, its character and manner of deposition if stratified, the direction and type of bedding, the extent

of fracturing, the occurrence of any soluble material or of any plastic material, the amount of weathering that has taken place and the strength of the rock as determined by crushing and microscopic tests. The principal requirements for bedrock are that it be solid and water-tight.

It is reasonable to assume that the rocks to serve as foundation for a dam should be at least as strong as the building material for the structure to be erected. Ordinarily this means at least equal in strength to good concrete. The actual crushing strength of the rock is generally determined in the laboratory of an engineering experiment station or in the larger geological laboratories. The geologist, however, must point out the bearing of geological structure on the strength of the rock-mass as a whole which taxes the capacity of the experienced man. It has often been found difficult to find geological talent tempered with practical engineering knowledge sufficient to put an engineering interpretation on geological indications, a fact which again is freshly stated (Hawley, 1936) as true in connection with the work of the State inspection of 950 dams in California during the years from 1929 to 1936.

In the western United States where a great number of large dams have been built or are under construction, a great number of excellent geological reports have been made during recent years. The Iron Canyon, Kennett, Pit, Stoney Gorge, Pardee, Pine Canyon, San Gabriel, El Capitan, Big Tujunga, are large California structures; Owyhee, Bonneville in Oregon; Grand Coulee in Washington; Boulder, Parker Dams in Colorado River. A great number of sites for major dams have been investigated by the State of California in connection with its Central Valley Project contemplating extensive water storages.

The movement of water in rocks is in the pore space along bedding planes and along faults and fractures. Obviously the amount of leakage or the rate at which the water flows under hydrostatic pressure through the rocks will depend on whether the rock is porous or impervious, whether thin-bedded or massive and on the amount of fracturing in the rock. When the flow of water is along bedding planes or fractures the leakage will be least when the strike of the bedding planes or fractures is parallel to the dam and greatest when the strike is transverse to the dam providing the dip of the strata is favorable. The direction of the strike of the strata or fractures is one of the most important factors in determining the amount of pressure grouting that will be required.

The slow seepage of water through a porous but insoluble rock such as a spongy lava or a scoria may cause no important loss from the reservoir, is more likely to decrease than to increase and can do no harm (Ransome). On the other hand even a small leakage through rocks that are partly soluble may so weaken the foundation of the dam as to cause disaster.

A characteristic feature of a fault is a seam filled with a clayey material known as gouge, which has been produced by the grinding together of the two rock walls during a movement on the fault. The seam may range from a fraction of a millimeter to several meters (Owyhee 3 meters) in thickness. It is generally accompanied on one or both sides by a zone of shattered

rock. Often the fault is water-tight but the shattered rock is likely to be permeable and the question of probable leakage under hydrostatic head must be considered. At the site of the Pardee Dam on the Mokelumne River in California for the East Bay Utilities District water supply system the rocks are schists of the bedrock complex (Ransome) which strike transverse to the river. The rocks are strong, are impervious to water and as no faults are present provide a very satisfactory foundation for a dam.

At the site of the St. Francis Dam, which failed on the night of March 12, 1928 and located in San Francisquito Canyon near Saugus, Los Angeles County, California, mica schist occurs on the east slope of the canyon and conglomerate on the west side. The contact is a fault plane (a true sedimentation contact, Willis), which parallels the canyon on the west slope about 18 meters above its base. On the fault is a seam of clay gouge and within the fault zone are numerous fractures filled with clay or gypsum. The fractured conglomerate completely disintegrates when immersed. The conclusion of the investigations was that the failure of the dam was caused by the disintegration of the fractured material.

Rocks as the ones at the St. Francis dam site held together by clayey material may be fairly hard when dry but becomes soft and plastic when wet and the recognition of this property is of utmost importance. A simple immersion test would have revealed the utter unsuitability (Ransome) of the conglomerate under the northwest abutment for the foundation of a high dam. Other rocks, particularly soft sandstone, show a decrease in strength when wet although the change is not often so pronounced as in the conglomerate at the St. Francis Dam.

Faults are likely to continue to be a plane of weakness and may show recurrent movement separated by long periods of quiescence. In some faults the gouge has become lithified and is now a fairly hard rock. The mere presence of a fault does not justify the condemnation of a site but it is important that its existence be known and that the dam be designed to meet future contingencies so far as this may be possible. Such features were introduced in the design of the Stoney Gorge Dam on the Orland project of the United States Reclamation Service in California where a fault traverses the dam in the stream channel. When the dams are founded on solid rock even a movement on a fault in the proximity does not necessarily spell disaster. The Crystal Springs concrete dam for the water supply of the City of San Francisco located near San Mateo, California, was not injured by movement on the San Andreas fault on April 18, 1906, although the fault line passes only about 270 meters west of the dam (Grunsky, 1931).

The location of any major faults in the vicinity is of course of great importance. To locate these faults might call for a regional examination of the geology. Often the course of a stream is on a fault along which there is a zone of rock weakness. In this case the fault is usually covered by stream gravel and in certain instances may not be apparent (Owyhee and Stony Gorge) when the examination is confined to the damsite but is discovered by a reconnoissance of the region. Should a concrete dam be

located on a fault a slight displacement on the fault might cause damage to the structure and possibly failure of the dam. If the structure is located close to a major fault the more favorable condition is that the fault be parallel to the line of the dam than transverse to it (Willis, 1922).

Failure caused by fault displacement is less likely to occur to an earth or rockfill dam than to a concrete or stone masonry dam as an earth dam is usually of sufficient size to take up the movement of the foundation rock. The maximum earthquake displacement recorded in California occurred along the Lone Pine fault in Owens Valley during 1872. During this disturbance the maximum vertical displacement was 7.50 meters and the horizontal displacement 3 meters. During the earthquake of 1906 the displacement along the San Andreas fault was horizontal the maximum amount being 6.40 meters. When the height of the dam is not great and its slopes comparatively flat an earth or rockfill dam may be considered a fairly safe structure when built across a fault. When no alternative site is to be found such a damsite may be employed and the type of dam to be built may be determined by geological conditions.

The Crystal Springs Dam already mentioned is located on the San Andreas fault. San Andreas Lake is close by on the same system and is retained by a high earth dam built across the fault. The fault strikes at right angles across the eastern side of the dam. Crystal Springs Lake is retained by a high concrete dam built parallel to the fault. The displacement causing the earthquake of April 18, 1906 occurred on this fault and produced considerable disturbance at the San Andreas earth fill dam over a strip 45 meters wide. However, the dam was not seriously injured and there was no loss of hydraulic head in the reservoir (Humphrey & Sewell, 1906). Probably a concrete dam at this location would have been damaged beyond repair. The concrete dam of Crystal Lake 45 meters high parallel to the fault and 270 meters east of it was not damaged during this earthquake.

It sometimes happens that a structure for which excavation work has begun is changed more or less in location as the excavation is opened up and the geologists have an opportunity to study the rocks more closely. On the Big Tujunga Dam in Southern California much preliminary exploration of the dam site was carried out, three consulting geologists and three consulting engineers being retained to check the findings. As a result of the thorough explorations one end of the dam was shifted 15 meters from the original location. The foundation rocks were explored in various ways the granite by means of several open shafts tunnels driven and diamond drill holes about 30 meters deep.

The Ariel damsite on the Lewis River in the State of Washington is in an ancient box canyon which once contained a waterfall. Following normal erosion within the canyon a change occurred which shifted the bottom of the falls to a point 22.30 meters below the present level. Thereafter sand and gravel were deposited to a depth of 38 meters on top of the native rock, a hard and strong basalt or andesitic lava.

Geological investigations prior to the construction period at Ariel were most extensive, the presence of active faults was feared but none were



Pit No. 1 Power Plant, Pit River Hydroelectric Development, northern California. Static Head 138.5 m from Elevation 1,013.8 to 875.3 m above sea level. Installation 70,000 k.v.a. Energy transmitted 320 Km at 220,000 volts to Vacaville Substation 50 Km southwest of Sacramento. Completed 1922.

Courtesy Pacific Gas and Electric Company, San Francisco, California.

discovered although the usual fissures were present. Test pits were dug on land and wash borings put down in the river to show the depth of gorge and foundation conditions and enable the preparation of plans and cost estimates. Various studies had disclosed a more favorable geological site farther upstream but proximity to transportation and to the city of Portland, Oregon, favored the lower site (Williams, 1931).

Wash borings and diamond drilling came into extensive use. Drill holes were sunk on lines at right angles to the canyon and 30 meters apart both upstream and downstream from the preliminary dam site. However, a study of these geological cross-sections resulted in locating the dam 38 meters upstream. As it was recognized that loose material in the streambed overlaid the country rock to great depth oblique drill holes were sunk from both abutments on the finally selected site and were continued until either intersected or passed each other entirely in rock. Vertical wash borings and core drilling through the river bottom then furnished an accurate profile of the rock. The Schlumberger electrical process was also used to determine depth of overburden and with it 90 per cent accuracy was obtained.

Unstable earth through overloading has been the cause of failure of some earth dams. Uncompleted embankments have slumped in a number of cases, notable being the Calaveras in California and Necaxa in Mexico, both of which failed during construction, in 1918 and 1909 respectively. These dams were both of the hydraulic fill type which carried within them the ever-present threat of soft and highly plastic masses of supersaturated clay. Slips have happened in several other embankments as the Lafayette dam near Oakland, California in 1928. Such failures have happened both during construction, during filling or when too suddenly drawn down as at Wachusett in the State of Massachusetts. But rolled fill embankments not complicated by impounded water have always been among the most stable and dependable of works of man as testify the thousands upon thousands of "Tanks" in India, Ceylon, Mesopotamia, etc.

The Lafayette Dam impounding an equalizing reservoir in the East Bay Municipal Districts water supply system partly failed through subsidence during construction on September 18-23, 1928. The dam was designed for a height of 40 meters and had reached 37 meters and 95 per cent completion in volume when the subsidence took place. Borings before construction indicated an alluvial deposit of clay frequently including sandy or gravelly content overlying the basic formation of the region. This formation is described in the geologists (Louderback) report as "of sedimentary origin composed of a large number of strata of conglomerate, coarse to fine sandstone usually with a clay matrix, sandy clay, clay and occasional volcanic tuff". Contact with a tight formation was made all along the dam center line, either by means of a concrete cutoff or the steel sheet piling driven beneath it in the streambed. The water table in the valley was 6 to 9 meters below ground surface.

With reference to the suitability of the foundation conclusions in the geological report on the site include the following: "Topographically the basin is excellent for a reservoir and dam site and the formations underlying

the soil and alluvium are satisfactory from the standpoint of structure and low permeability. Percolation through the alluvium of the valley floor at the dam site should be guarded against, also the sliding effects of the Orindan clays at the dam site."

Subsidence amounting to about 6 meters took place at the center of the dam and a shifting downstream of many thousand cubic meters took place. No ponding was used in the placement of the material and only a very small quantity of water was in the reservoir. The material in the dam was dry and very solidly compacted with trucks rollers and petrolithic rollers after being thoroughly wetted down with hose. Selected material was placed in the center, clay loam and sand for the upstream side and loam clay gravel and stone for the downstream side.

The geological investigations, report, judgment and opinions on the ever larger and larger water conservation projects undertaken must be of the very highest order and only serious study and wide experience can qualify a man for such work. Writes one geologist (Bryan, 1929): "The study of a reservoir site involves large responsibilities because remedial measures against leakage are seldom possible. His conclusions can not be tested save by the expensive method of constructing and filling the reservoir. If he approves the site and after construction the reservoir fails to hold water the investment is lost, if he condemns the site and no suitable substitute can be found the project is abortive . . . It, therefore, behooves the geologist charged with such duty to determine the groundwater conditions with exactness, to require the drilling of test wells at critical points and then analyze his data with care and in humbleness of spirit." Writes Ransome, eminent scientist, theoretical and economic geologist: "Dam sites which from the geological point of view are ideal in all respects are exceedingly rare if any exist. On the other hand, it is perhaps not an unduly optimistic tribute to the skill of modern engineers to state that a dam may be built successfully on any site if the geological conditions are known and if no limit is placed on cost. In practice the construction of a dam involves compromise and adjustment between these extremes. The one great point to be emphasized is that the engineers should have before them as complete and reliable presentation of the geological conditions as it is possible to obtain." The same author for many years consulting geologist to the United States Reclamation Service on many large western dam projects including the Owyhee and Boulder Dams in his presidential address before the Society of Economic Geologists, Cleveland, Ohio Meeting on December 30, 1927, said: "Again leaving for the moment the subject of ore bodies we as economic geologists or as geological engineers are sometimes asked to determine whether a certain reservoir site will hold water behind a dam 300 or 400 feet (90 or 120 meters) high. As far as I know there are no experimental or quantitative data on record that will furnish a basis for answering this question. The geologist must make the best prediction that he can under the circumstances perhaps aided by some knowledge or behavior of reservoirs previously filled in similar rocks . . ." and "no one can truly

become an economic geologist without first becoming a good geologist—a fact sometimes overlooked . . .”

Failure of dams have been numerous over 300 major structures having failed being on record (Cooper, 1936). One of the earliest recorded failures is Dam del Gasco on the Guadarrama River in Spain, which occurred in 1799. The dam was a straight gravity type structure consisting of two walls 2.70 meters thick connected by cross walls. The compartments were filled with clay and stone. During a flood water overtopped the dam swelling the clay and forced over part of the front wall (Wegmann, 1927). All conceivable types of dams have failed with the exception of pure arch dams, although many freaks of this type are in existence (Jorgensen, 1920). One of the largest dam disasters in history was the Johnstown Dam disaster on May 31, 1889. The earth structure on the South Fork of the Conemaugh River above Johnstown, Pennsylvania, was 284 meters long, 23 meters high with a 3 to 3.60 meters crest width. It was made of impervious soil in the upstream half and a rock gravel and sand fill in the lower half. There was no core wall or puddle of any kind. The cause of failure was overtopping contributed to by a lowering of the crest the closing of a pipe tunnel outlet and the obstruction of the spillway. With more than 2,000 lives lost this disaster has been characterized as the worst in history resulting from failure of a man-made structure.

In the Walnut Grove Dam disaster on February 22, 1890, at Prescott, Arizona, 150 lives were lost; in the Austin, Texas Dam failure of April 7, 1900, 8 persons were drowned. At the Lower Otay Dam at San Diego, California on January 27, 1916, 30 lives were lost.

On August 13, 1935 the smaller of the Zerbino dams forming the Ortiglieto Reservoir on the Orba River, above Molare in northern Italy, failed. Excessive rainfall and the non-functioning of regulating facilities caused the 12 meters high dam to overflow to considerable depth, according to (Du Bois, 1935) overloading the structure and in the absence of downstream safeguards against underscour from the tremendous masses of water falling over the dam causing it to collapse. Erosion of the rock where the small dam had stood, on a ridge across the river channel, released still more water. In this case the potentiality for disaster of the small dam was there in far greater ratio than the comparatively small height of the dam would indicate, through the possibility of the outrushing waters eroding the soft schistose rocks forming the dam foundation. Official Italian reports after the disaster placed the loss of life at more than 100 and large material losses were caused, buildings, bridges and power plants wholly or in part destroyed as well as agricultural land ruined (Probst, 1935).

The largest European dam failure of recent years was the Lake Gleno, Dam, a combination multiple arch and gravity structure near Bergamo Italy on December 1, 1923. The dam was 44 meters high above the stream bed, 264 meters long of which 75 meters was a central curved portion, the remainder being straight tangents. The central part which failed had a gravity base of stone masonry surmounted by multiple arches of reinforced concrete. In all there were 25 arches of which 9 fell. Failure was due

to inherent weakness in the design and extremely bad execution of the construction work. Rock foundation in the deepest part of the valley had a downstream slope and had not been levelled, stepped or notched before building the masonry block. A gravity dam had originally been planned, hence the masonry plug in lime mortar in the deepest part of the gorge. This masonry plug in arch-form had no end support and was broken through by a drainage passage. This block evidently slid on the rock bed. Six hundred persons lost their lives.

The St. Francis Dam catastrophe on March 12-13, 1928 is one of the largest dam disasters that have occurred. The dam located in San Francisco Canyon emptying into the Santa Clara River, Los Angeles County, California. The dam was a concrete structure of gravity type arched in plan on a 150 meters radius. The maximum section was 62.50 meters high and had a base width of 53.60 meters. The foundation pressure at the toe was limited to 9.75 kilograms per square centimeter (10 tons per square foot). Concrete was taken to weigh 2,240 kilograms per cubic meter (140 pounds per cubic foot) and allowance was made for hydrostatic uplift. Excavation for the foundation extended 9 meters below streambed at midchannel and to lesser depths at higher elevations. About 500 lives were lost and very large property damage resulted.

Immediately after the failure the Governor of California appointed a Commission of Investigation. The commission consisted of two eminent geologists and four civil engineers of high standing. The first and outstanding conclusion of the Commission reads: "Failure of the St. Francis Dam was due to defective foundations."

Regarding geological conditions it was found that the dam was placed astride of a fault or contact between reddish conglomerate and a fairly uniform mica schist. "In many places the schist has been strongly sheared commonly along planes roughly parallel with the schistosity or planes of lamination. Along these shear zones the rock has been changed to an exceedingly fragile flaky material that can be readily excavated with the pick. From a structural point of view such sheared schist is extremely weak material."

After drying out for a few days the surface of the conglomerate on the right abutment "showed plain smooth surface when broken and some of the hardest specimens rang under the hammer. Many of these, however, go to pieces when immersed in water for a few hours and samples taken over a considerable area have gone to pieces immediately upon immersion. Material from the gouge along the fault between the conglomerate and schist rapidly becomes soft and unctuous when immersed."

The contact between the conglomerate and schist on the right bank showed considerable ancient movement. The fault had long been known but no recent movement had occurred. On the left bank the water carried away a large amount of the schist not only on the sidehill of the canyon or along the abutment but also in the bottom.

The general strike of the schistosity is parallel to the course of the canyon at the dam site. The lamination of this schist is nearly parallel with the

steep slope of the left bank, the slope in fact being conditioned largely by the schist laminations which were also responsible for the landslide. So far as evidence can show the dam itself was perfectly sound both in design and in construction but it goes without saying that the best dam in the world, if erected on a weak and leaky base, is a public menace.

The disaster caused by the failure of the St. Francis Dam will long be remembered. Within a brief interval of time hundreds of lives were lost, a fertile valley was reduced to a scene of desolation and property valued at many millions of dollars was destroyed. Probably the disaster furnished the initial impulse to the great activity of geologists and engineers to try to improve the design and construction of dams that has taken place during recent years, both in America and in other countries. These two last mentioned major dam failures with accompanying loss of life and property has done more to arouse geologists to more seriously take up the study of the causes of failure and the means of preventing future disasters.

When an analysis is made in accordance with causes of failure, it is found that inadequate foundation represent 28 per cent, insufficient capacity or design of spillway 33 per cent, improper design of appurtenant works 12 per cent, the improper design of the dam 19 per cent and miscellaneous causes contributed to the remaining 8 per cent of the failures. These percentages were arrived at in a study of 100 dam failures since 1900 undertaken in the office of the State Engineer of California soon after the failure of the St. Francis Dam in 1928.

A few years ago the First International Congress on Large Dams was held in Paris. The Second International Congress on Large Dams was held in connection with the Third World Power Conference in Washington, September 7-12, 1936. On the subject of dam foundations 11 papers were submitted by delegates from France, Switzerland, Great Britain, Japan, U.S.S.R., Germany, Sweden and the United States.

The importance of advance geological investigations of dam sites was noted as universally accepted. Attempts to classify rocks for foundation qualities have been made. The danger arising from old valleys buried under glacial deposit and the need for percolation studies in pervious ground are recognized. Tests of the strength of foundation materials appear to be imperfect as yet in the case of both rock or loose ground. Pressure grouting to correct foundation conditions (with cement, asphalt, clay and chemicals) receives very thorough attention throughout the world. Cutoffs and blanketing are also used to improve foundations.

The important field of earth dams was presented in fifteen papers by delegates from Italy and Czechoslovakia in addition to the countries mentioned above under foundations. Foundation stability at shallow and greater depth was discussed, risk of sliding of embankments by rapid drawdown, the importance of checking earth dam theories by observation, etc.

The conclusions were that in regard to dams the foundation is the first essential. More dams have failed because of bad foundations than from any other cause and even though foundation conditions today receive more

thorough attention than formerly yet it is a fact that nearly all of the dam disasters of the last decade were brought about by foundation defects. Rock weakness underflow and erosion need to be more illuminated, a task in which the geologist will play a most important role.

Tunnels of large and small dimensions are frequently employed in hydraulic construction, their purposes may be divided into bypass tunnels for diversion of the stream during construction of the dam, outlet or diversion tunnels for drawing off water for use, spillway tunnels. Tunneling commonly incurs geologic difficulties unless examinations are made beforehand with these in mind. The ideal situation is to have solid rock free from shattering by faults or joints which might serve as a channel way for ground water from above and which would necessitate timbering, and free flow clay or gouge layers which upon swelling dislodge the timbering.

So far as the construction of hydraulic tunnels is concerned, these tunnels are like tunnels of any other kind. The location of these tunnels, however, is subject to many ingenious arrangements by which one tunnel may be made to serve more than one purpose, as for instance, at the Boulder Dam where two of the four 17 meters diameter tunnels first served for diversion of the river and later were used for the installation of the 15.25 meters inside diameter steel penstocks for the power plant. The entrance to a tunnel from a valley or canyon side often causes difficulty on account of soft or disintegrated rock close to the surface and several alternatives might be considered in the location.

A geological report is of considerable value to the engineer when making a location of a tunnel for water power development, public water supply or irrigation. It is, of course, advantageous to drive a tunnel in hard, firm rock and to avoid caving, moving, swelling or wet ground. This location can best be determined from the study of a detailed geological map and cross-sections of the area adjacent to the tunnel site. Soft strata, axes of folds, contacts and fault zones are avoided when practical. By study of the formations and their structure the occurrence of unusual quantities of water or gas can generally be foreseen. The difficulties of making correct prediction and interpretation are generally greater in tunnel location than in mining as there are no extensive excavations available at tunnel sites from which geologic data may be obtained. When the cover is not too great core drilling is generally resorted to as they are useful in making accurate predictions.

In case the area is occupied by sedimentary rocks alternating beds of sandstone and shale may occur. If the tunnel is driven parallel to the strike of those beds the sandstone is to be preferred wherever possible, as the shale may cave or swell and cause high maintenance costs. When formations are folded it is sometimes advantageous to keep away from the axis of the fold, for the rocks are weakest along this axis. A contact is a line of weakness and should be avoided in the location as the rocks may have weak and shattered areas due to altered conditions of the rock and to unconformities. A fault should also be avoided on account of the possibility of movement that might endanger the structure. Underground water

often flows in synclinal folds and knowledge of these conditions is often the means of saving in cost of the project.

Tunneling is a complex art. Of recent years a great number of long hydraulic tunnels have been driven in the most varied formations and with use of many types of equipment. Geological investigations are always undertaken before starting construction on a large project and has always proved valuable regardless of the degree of accuracy of the geologist's prediction.

Tunnels of large diameter through earth and soft formations generally cost more than a same size bore tunnel through solid rock, the former requiring a greater or lesser amount of timbering while the hard rock tunnel requires little or none, as in the case of the 17 meters diameter tunnels at Boulder Dam before-mentioned. Tunnels driven in the formations of the lava-covered Plateau in north-eastern California through which runs the Klamath River and the Pit River, require very heavy timbering, carry a large flow of water, often but not always, and require an unusually heavy reinforced concrete lining. On a 6 meters diameter tunnel in this region designed by the writer, it was necessary to re-timber and partly re-excavate a length of driven and well-timbered section of 130 meters through a section of unusually heavy ground before the concrete lining could be placed. The increased cost amounted to about $2\frac{1}{2}$ times the original estimate. On a nearby project with a tunnel of 7.50 meters rough diameter and of 6.50 kilometers length great water difficulties were encountered.

Hydraulic tunnels in the Sierra Nevada of California more or less traversing the basement complex (Ransome) of rocks have encountered much less difficulties and many such tunnels stand up and answer their purpose unlined. The higher tunnels of the Hetch Hetchy water supply system for the City of San Francisco are to be mentioned as such, as well as the 20.80 kilometer long Florence Lake power tunnel of the Big Creek hydroelectric system of the Southern California Edison Company. It follows the north contour of the Kaiser range which lies in the north-eastern part of Fresno County, California at an altitude of about 2,200 meters. Greater difficulties were encountered on the longest hydraulic tunnel in operation, the Coast Range tunnel of the before-mentioned Hetch Hetchy water system. This tunnel crosses the Hamilton and the Diablo Ranges from the west side of the San Joaquin Valley to the east side of San Francisco Bay at its southern end, about 38 kilometers south of the city. It is 40.60 kilometers long and is intended to carry the water to the crossing of the San Francisco Bay at the narrowest point. Here in places the ground penetrated was very unstable and had a pronounced tendency to swell. This condition was met by lining the tunnel with gunnite concrete as soon as possible after opening up and exposing the ground to the atmosphere. Water-bearing seams were made tight by forcing grout into them by compressed air. Occasional occurrences of methane gas presented serious difficulty. This is the gas that constitutes some 80 per cent of the natural gas that is now used in California for heating purposes. A mixture of methane gas and air in certain proportions is highly explosive and after a serious accident in the tunnel

much of the construction equipment had to be changed to satisfy the inspecting engineers of the United States Bureau of Mines. The delay in completion of the tunnel was more than one year.

Several hundred kilometers of hydraulic tunnels for water power, public water supply and irrigation have been built in California, of which well over 100 kilometers are incorporated in the above-mentioned Hetch Hetchy water supply system for the City of San Francisco. Altogether 150 kilometers aggregate length of tunnels will form part of the new aqueduct now being built from the Colorado River at Parker, Arizona to Los Angeles for the Metropolitan Water District formed by the City of Los Angeles and a number of nearby cities in Southern California. This conduit will cross the active San Andreas fault and great care will be exercised in location of the water tunnel across this rift.

The hydraulic tunnels in southern California are often located in geologically young formations and generally require lining with concrete plain or reinforced. Many foothill tunnels along the Sierra Nevada also need this type of construction where they to a greater or lesser extent run through the younger sedimentary formations. Within the Sierra all longer tunnels have been driven without great difficulties. In the northern part of the Sierra Nevada on Feather River the volcanic formations set in and have caused difficulties in tunnel driving of the same kind as before-mentioned generally encountering large flows of water and often heavy ground.

The Coast Ranges have only a few water tunnels, the most recently constructed being a unit in the water supply system for the City of Eureka on the coast of northern California. This tunnel is about 730 meters in length. Two tunnels, the Lafayette and the Claremont for the East Bay Cities water supply system, traverse the Coast Ranges due east of these cities. The Claremont tunnel 5.50 kilometers long, traverses gravel sandstone and shales of Pliocene age and sandstone of Cretaceous age. Owing to the porous nature of the lavas, to the fact that they were badly fractured and to the synclinal structure of the formation, water in large quantities was encountered as predicted by the geologist. At times while driving through the lava the water was 1.20 meters deep in the tunnel and as the invert of this bore is below ground level it all had to be pumped. To this being below gravity drainage, was also due the accident on Thanksgiving Day, October 25, 1926, when the nearby San Pablo Creek, swollen by a freshet, overflowed and filled the tunnel, drowning the tunnel-driving crew of ten. Gas was also encountered in this tunnel.

In the Lafayette tunnel bad ground was encountered. For most of the length it is near the surface where rocks are more likely to be fractured than at greater depth. The formation encountered included poorly cemented sandstones, shales and conglomerates. The structure is that of a plunging anticline, the axis of which is crossed by the tunnel. On account of folding the conglomerates were badly broken and did not stand well, while the sandstones and shales, being more plastic, were less disturbed.

Spillways, aqueducts, flumes, pipe lines, and siphons are other hydraulic structures whose location should be made with the aid of a geological ex-

amination. Faults need to be located, as there are the possibilities of displacement on the fault, in which case a line conduit or other structure would be damaged or destroyed.

Intensive study has been given to earthquake resistance by seismologists and engineers, especially since the time of the Tokio earthquake of September 1, 1923, and the Santa Barbara earthquake in California of June 29, 1925. The feasibility of designing earthquake proof structures was demonstrated in the Tokio earthquake. Three buildings, especially designed to resist earthquake, came through the Tokio disaster undamaged. Geologically the location of the structure is of great importance. The intensity of the shock will depend upon the proximity to the earthquake fault and upon the character of the foundation work. If close to the fault the intensity is much greater than farther away from it. (This has not been fully agreed to by some prominent seismologists and structural engineers.) The shock intensity is least when the structure is built on solid rock and greatest when located on filled or marshy ground.

After a thorough study of the Tokio disaster it was found that when the vibration period of a building coincides with that of the earthquake the building may suffer terribly from the harmonizing effect of the two vibrations (Naito Tashu, 1927). A severe earthquake usually has a vibrational period of from one to one and one-half seconds although periods as large as two or three seconds occurred in Tokio in 1923 (Clark, 1933). A well-constructed seven or eight story building would have a natural vibration period of from 0.4 to 1.0 second. Therefore, a structure should be built as rigid as possible by the use of diagonal bracing or shear-resisting walls in order that its period be small, thus preventing its natural vibration from synchronizing with that of the earthquake. In California, all dams, bridges, buildings, etc. are now being designed with an allowance for earthquake impact and all existing important structures, including all schools, have been re-built and reinforced. Where a seismic factor is included in the design, the usual allowance is for a horizontal force in any direction of 0.1 g.

The Santa Barbara earthquake of June 29, 1925, provided a number of examples showing how structures well designed and constructed withstood the shock. The Southern Pacific Railroad bridge across Dos Pueblos Canyon illustrated the strong resistance to earthquakes of well-built steel structures (Kirkbride, 1925) as it affected the railroad. This bridge is 202 meters long and 20 meters high at the highest point. A witness during the earthquake describes how the bridge vibrated in an alarming manner and that it looked as though the entire structure would topple over. When the vibration ceased this structure returned to its original position, hardly any damage having resulted.

The Santa Barbara Dam was destroyed by this earthquake. This dam was a small earth dam 6 to 7.50 meters high. It gave way and a few thousand cubic meters of water which had filled the reservoir created by the dam were released. It had been built of clayey material and its upstream slope had been faced with concrete. As the concrete revetment was not

water-tight the upstream part of the embankment had been fairly well saturated. The reservoir was full at the time of the earthquake. All conditions were, therefore, favorable for the yielding of the dam under the influence of the earth tremor. The embankment had lost weight by hydrostatic uplift and had lost cohesion by saturation to an extent which put it in a condition to be shoved off its base by the pressure of the water in the reservoir. All that was needed was the acceleration imparted by the earthquake vibration and the dam slid from its foundation—a portion thereof much flattened out being swung out of position as though it had been a gate opening on hinges.

The foregoing discussion of geology as related to problems on water collection, conservation and utilization has shown the importance of geological investigations, reports and mapping in connection with hydraulic works, especially in the first stages of a development. In many instances of the past the geologist has been called to come along with the coroner for the post mortem inquest, as was the case at the St. Francis disaster, at Gleno and numerous other instances.

It is necessary for the hydraulic engineer to know, whether a topographically seemingly favorable reservoir site will hold water, whether the rock formations in a river channel are suitable for a proposed dam structure or about the ground and water conditions to be expected in a projected tunnel bore. "Any time the engineer digs a hole in the ground he is investigating the local geology" (Bryan, 1929), and for the smaller problems he can so by experience learn the geology he needs to know. As projects have grown in magnitude, the difficulties as regard foundations, watertightness, etc. have increased manifold.

It has become the rule rather than the exception in an increasing number of undertakings to call in the experienced geologist to give the benefit of his special knowledge and ability to reduce the tests required, be it borings, test pits, trenchings, by locating them in significant places and to make correct interpretations upon the findings. On the engineer falls the responsibility for the design of structures and usually also for the cost of investigations. Formerly the employer was rather tardy in acceding to the engineer's suggestion for expert geologic advice. The writer once upon such suggestion was told: "Go ahead, call in the rock professor, we will pay the bill, but remember, son, you are responsible to us that the dam stands up." The geologist was called in and the concrete saved in the design paid his fee a few times over. There seems to be a tacit assumption in many quarters that the civil engineer's training fits him to solve all geological problems he may encounter in his work but that idea is fallacious. Given the true facts of the geological conditions the engineer can build in most locations, but he cannot be expected to be an expert geologist. Writes geologist (Longwell, 1928) "Geology is a complex subject. Many of its problems tax all the resources of men who have devoted the best years of their lives to its study. Without question, most engineers charged with the building of dams and other large structures would welcome cooperation by competent geologic specialists."

PART TWO

California.—Basic Features Bearing on Water Conditions in the State.—Water Resources.

I. Geographical Data.

The State of California is the second largest of the forty-eight States of the Union and is located in the extreme south-west of the continental United States. The geographical form and position may seem to be so well known as to demand no mention but there are certain facts concerning them that should be kept in mind and certain errors in the general conception that should be pointed out. Most of these arise from the fact that the great bend in the coast line at Cape Mendocino is not clearly recognized unless attention is specifically drawn to it. The usual idea of California is that it is an extremely long state extending due north and south along the Pacific coast, the fact that the coast line really runs north-west and south-east is overlooked. On account of this fact, although it is only 300 kilometers wide, the meridian passing through its westernmost point Cape Mendocino $124^{\circ}26'$ west of Greenwich is about 940 kilometers west of that passing through its easternmost point near Parker on Colorado River in longitude $114^{\circ}7'W.$; and although the parallel forming its northern boundary $42^{\circ}N.$ is 1,055 kilometers due north of that at National City, the most southerly point in the State in latitude $32^{\circ}32'N.$ its maximum length from the point where the California-Oregon boundary strikes the coast to the point where the California-Mexican boundary strikes Colorado River is fully 1,320 kilometers. The westernmost point of the State is almost as far west as Cape Flattery in Washington, the extreme western point of the United States. Because of the bend in the coast the easternmost point at Parker on Colorado River is due south of the eastern boundary of Nevada, of central Idaho, and of western Montana.

California is bounded on the north by Oregon along the $N42^{\circ}$ parallel through a distance of 342 kilometers from the Pacific Ocean east to the $120^{\circ}W$ meridian. Along this meridian it is bounded by Nevada south to latitude $N38^{\circ}58'$ near the southern end of Lake Tahoe through a distance of about 337 kilometers. At this point the boundary line deviates from the 120th meridian an amount of about $49\frac{1}{2}^{\circ}$ to the south-east running in that direction bounded by Nevada through a distance of about 645 kilometers to the intersection of the 35th parallel with the approximately north-south oriented Colorado River. It is bounded by the State of Nevada through a

total distance of about 985 kilometers. South of the point mentioned the boundary follows the middle of the Colorado River with Arizona to the east, through a distance of over 380 kilometers down to Yuma on the Mexican border. Westward from Yuma it is bounded by the Republic of Mexico to a point on the shore of the Pacific Ocean at National City in latitude $N32^{\circ}32'$. On the west it borders upon the Pacific Ocean through its whole length of about 1,500 kilometers or closer to 1,900 kilometers depending upon whether the smallest bays, indentations, and meanders be considered or not. The boundary on the Pacific Ocean is, therefore, of practically the same length as the total continent-ward boundary. The south and west boundaries, territorial waters included are part of the national boundaries in these directions.

Lying between the parallels $N32^{\circ}32'$ and $N42^{\circ}$ or almost nine and one-half degrees of latitude the maximum length on the meridian is 1,055 kilometers. Due to its peculiar shape, being the longest and slenderest of all the states absolutely as well as relatively, the distances within the State are great, the longest straight diagonal line that can be drawn within its borders approximates 1,340 kilometers (Basel—Danzig). The extreme longitudinal limits extend from the most easterly point in San Bernardino County in an eastward bend of the Colorado River in $W114^{\circ}7'$ to the most westerly point at Cape Mendocino in $W124^{\circ}26'$ the overall geographical extremes are therefore: north—south $9\frac{1}{2}^{\circ}$; east—west $10\frac{1}{4}^{\circ}$.

The breadth measured on the parallel varies from its greatest on a line east from point Arguello in Santa Barbara County eastward to Colorado River in San Bernardino County a distance of about 575 kilometers to 245 kilometers at the Mexican boundary from Yuma to the Pacific Ocean and 342 kilometers at the Oregon boundary. The least breadth measured normal to the trend of the length of the State is from Golden Gate to the California-Nevada boundary-knee at the southern end of Lake Tahoe a distance of about 255 kilometers. The average width of the State is, therefore, about 300 kilometers. The coast line of California makes up about 70 per cent of the continental United States' boundary upon the Pacific Ocean exclusive of Alaska.

The coast line has comparatively few indentations the notable exceptions being at San Diego, San Pedro, Santa Monica, San Luis Obispo, Monterey, San Francisco, Bolinas, Tamales and Humboldt Bay.

For practical purposes it is customary to designate the boundaries of the State of California as follows: on the north, the State of Oregon; on the east, the States of Nevada and Arizona from the latter of which it is separated by the Colorado River; on the south, Mexico; on the west, the Pacific Ocean.

The aggregate area of the State of California is reported by the United States Secretary of the Interior as being 158,297 square miles, or 409,989 square kilometers, of which the land area is 155,652 square miles, or 403,139 square kilometers, the difference 2,645 square miles, or 6,850 square kilometers constituting water area. Compared in area with the eastern states this is almost as large as New York, Pennsylvania and the six New England

states combined. Compared with some European countries it is 87 per cent of the area of Germany, 91 per cent of the area of Sweden, more than one-third larger than Italy or it is ten times the area of Switzerland.

Politically the State of California is divided into fifty-eight counties varying in size from the largest, San Bernardino County in southern part of the State with an area of 52,252 square kilometers, to Santa Cruz County at the north of Monterey Bay with an area of 1,126 square kilometers, to the smallest, San Francisco County, with an area of 109 square kilometers. The average size area of the counties is 2,672 square kilometers.

II. Physiography.

The physiography of California has been stated as simple, its main features few and bold (Chapman, 1932). The outstanding geographical features are the mountain ranges, the Sierra Nevada, traversing about half the length of the eastern central part of the State, the Coast Ranges, which, as the name implies, extend along the western border roughly paralleling the coast. These two mountain chains uniting on the south in latitude $N34^{\circ}45'$ near Fort Tejon and on the north about 75 kilometers south of Mount Shasta in latitude $N40^{\circ}30'$, enclose a great Central Valley comprising the valley of the Sacramento River to the north and the San Joaquin River to the south with a combined length of 750 to 700 kilometers and a breadth varying between 60 and 120 kilometers. Through this Great Valley flow these two streams carrying the waters form an 800-kilometer stretch of the western slope of the Sierra Nevada and the southernmost Cascade Range as well as the insignificant runoff from the eastern slopes of the Coast Ranges, eventually finding their way into Suisun Bay through the Straits of Carquinez, the San Pablo Bay, San Francisco Bay, and through the Golden Gate to the Pacific Ocean. To the south of these mountain chains lies Southern California, about one-third the area of the State. To the east and north-east lies the Great Basin, to a large extent on California territory.

The quite divergent character of the various portions of the State relative to physiography, climate, precipitation, evaporation, surface waters, ground waters, flora and fauna, has always required that it be differentiated, divided into areas within which there was a substantial continuity as regards any or all of these particular characteristics. So it has come to pass that a multitude of divisions, into regions, or into sections, has been set up and used at different times and for the same, or for varying purposes.

Early (Whitney, 1865) makes differentiation into three major portions: the Sierra Nevada, the Coast Ranges, the enclosed Great Valley. Another subdividing (Ratzel, 1878), speaks of five parallel lines spaced 88 kilometers and running $N.31^{\circ}W.$ the middle line laid at the western foot of the Sierra Nevada from Visalia to Red Bluff. The first line east following the main divide and the second line at the east foot of the mountain from Klamath Lake to the confluence of the Gila with Colorado River. The first west line at the eastern foot of the Coast Ranges from Kern to Clear Lake and the

westernmost line to follow the coast of the Pacific from Cape Mendocino to Point Arguello. These five parallel lines would fairly represent the boundaries of the four large natural, physiographic regions (natürlichen Landschaften) of California; East slope of the Sierra Nevada; West slope and foot hills; the Valley of California; the Coast Ranges. This method is similar to Whitney's with the further dividing the Sierra Nevada along its crest. Pointing out the non-uniformity in physiographic character of the Pacific Slope (Holway, 1915) considers a fair approach satisfying various sciences the division into: the Coast Ranges; the Pacific Valleys, the Sierra-Cascade Ranges, and the Arid Plateaus. For study of particular agricultural adaptations (Wickson, 1923) obtains the following subdivisions of California: North-west Coast Region; Central Coast Region; Southern Coast Region; Interior Valley Region; Mountain and Plateau Region. In his *Geography of California* (Fairbanks, 1925) introduces seven natural Provinces adding two to the list just mentioned, essentially by adding the Klamath Mountains and the Great Basin. The Association of American Geographers have adopted a physiographic subdivision prepared 1914 (Fennemann, 1931) in cooperation with the United States Geological Survey who issues a map of this subdivision plan "Physical Divisions of the United States," as a public document.

For purposes of this study the subdivision according to this map will be followed except where regarding water resources it will be found more appropriate to adopt the "basin method" as used by the United States Geological Survey in their publications on water yield and stream flow. A similar subdivision has also been adopted by the National Resources Board (Huber, 1935), when taking an inventory of western water resources.

The area of California in addition to the area in southern Oregon draining into and through California, will be treated, therefore, throughout this study according to sections or basins designated as follows:

- | | |
|----------------------|-------------------------------|
| a. North Pacific | e. Sacramento Basin |
| b. San Francisco Bay | f. San Joaquin Basin |
| c. Central Pacific | g. Great Basin (including the |
| d. South Pacific | lava-covered plateau) |

These sections, with minor differences, approximate the physical divisions as first suggested and worked out by Fennemann and used by the United States Geological Survey. The location and extent of each one of these subdivisions are shown on sketch (Fig. 1). A somewhat detailed description of the physiography of each subdivision of the State will be given.

North Pacific:—The North Pacific coast section as here described begins with a narrow point at the Golden Gate and gradually widening extending north to the Oregon boundary and includes the Klamath River watershed in southern Oregon. The area approximates 68,000 square kilometers.

This section is mountainous and hilly being covered by the Coast Range and the Klamath Mountains. Generally the ranges lie approximately parallel to the coast or rather diverge to the west and disappear under the ocean. The range in the extreme north-western part of California forming



Fig. 1.

the divide between Smith River and Klamath River drainage is called the Siskiyou Mountains. These mountains also extend eastward along the course of Klamath River. To the south, with a general east and west direction, are the Scott Mountains and farther south lie the Trinity, Bully Choop and Yolla Bolly Mountains. Farther to the west along the eastern side of Mad River are the South Fork Mountains and still more to the south an area of sharply cut ridges and canyons locally called the Wildcat region

forms part of the Mendocino Range. A system of ridges continues southward through the section of the coastal system but these mountains are not known by a distinctive name (Waring, 1914). South-east of those is the St. Helena Range.

The Klamath Mountains, generally speaking, are less than 1,500 meters in elevation but the higher peaks of Scott and Yolla Bolly mountains reach 2,000 meters in elevation. The Salmon Range is the highest and most rugged with several peaks more than 2,700 meters in elevation above sea level.

The valleys of the region are relatively small and irregular, although the Eel River Valley has great area and the flat lands at Humboldt Bay are broad and rich. Farther east the Scott Valley and Shasta Valley have considerable areas of flat lands and in the vicinity of Klamath Falls extensive land areas, reclaimed lake beds, are under irrigation. The littoral of the section is a series of grassy wind-swept benches carved out of the seaward border of an elevated and maturely dissected peneplain lying from 500 to 600 meters above sea level. Boldness and irregularity in detail are characteristics of this cliffed wave-eroded coast, which presents a succession of headlines and reentrants, Stacks, chimneys and large rocky island residuals project beyond the rocky headlines. Caves, arches, windows, have been carved. The prevailing winds form dunes from the sands blown from the shores, especially around Humboldt Bay. The general lines of the coast are related to the structures that also determine the major land features. The structure is likewise reflected in the remarkable parallelism of the main stream valleys in the coast ranges (Lawson, 1894). The sea is even now actively planning the land border and perfecting a submarine bench cut across upturned strata visible in part at low tide (Hoover, 1923), and the depositional features are small and limited to the short stretches that run south-west. Conspicuous are the ancient marine terraces, about which more under geology.

The total agricultural area in the North Pacific section is estimated at not over 200,000 hectares. The section on the whole, as stated, is very mountainous and hilly in character and is heavily covered with timber and undergrowth. Of grains raised, barley and oats are the most important, corn and sorghum are likely not to ripen for lack of heat (Wickson, 1923). The chief industry is dairying with grazing and root crops. Scott Valley is partly irrigated, Shasta Valley being still more in the rain shadow of the mountains is more extensively irrigated. Apples and berries succeed well. In the Klamath Falls region the potato is extensively grown.

San Francisco Bay:—The San Francisco Bay section as here described has an area of 10,000 square kilometers bordering upon and including San Francisco Bay proper. About ten per cent of the area are gently sloping coastal plains and balanos, relatively low rolling foothills, within which lies a number of small valleys. These small valleys and the coastal plains area make up the agricultural land. Within this section on the San Francisco Peninsula, whose structure consists of the San Mateo Mountains, lies the City of San Francisco, the Byzantine Glory on the Golden Gate (Mencken), with a population of approximately 650,000. On the eastern

shore of the Bay lie the East Bay Cities, comprising Oakland, Alameda, Berkeley, Richmond, Hayward, Emeryville, together with a number of smaller communities having an aggregate population of approximately 600,000. Here the Berkeley Hills, a continuation north of the Mount Diablo-Hamilton Range, constitute the most notable physiographic feature.

In the southern portion of this section lies the fertile, agriculturally highly developed Santa Clara Valley. This valley lies south-east of San Francisco and is bounded by the Santa Cruz Mountains paralleling the coast on the west and by the Mount Hamilton Range stretching southward between Santa Clara Valley and the valley of the San Joaquin, on the east. The length of the valley in a south-easterly direction is about 100 kilometers and the average breadth about 30 kilometers. In this valley and in adjacent foothills lies the largest and most important agricultural area of the San Francisco Bay section with an extent of about 54,000 hectares.

Only a small area of the agricultural lands of the section is devoted to grain and forage crops. Fruit growing is the more important, prunes coming first with about 28,000 hectares or 50 per cent of the whole agricultural area. The next important fruit is the apricot, with 7,500 hectares, pear with 3,100 hectares followed by 2,100 hectares of cherries. The grape, walnut, apple, plum, almond, fig and olive are grown.

Central Pacific:—The Central Pacific section of about 31,000 square kilometers area includes slopes along the coast south of San Francisco Bay section. The Coast Ranges in this section in general trend parallel to the coast. Among them are the Santa Cruz Mountains; the Diablo Range, which separates San Joaquin and San Benito Valleys; and the Gabilan Range, which separates the San Benito and Salinas Valleys farther to the south. The Santa Lucia Range forms a mountainous region south of Monterey Bay, and to the east of it farther south lies the Temblor Range, bordering on the San Joaquin Valley. The San Rafael, San Emigdio, Mount Pinos, Santa Ynez Mountains, the latter in an almost west-east direction along the Pacific Ocean shore easterly from Point Conception are at the southern end of this section. Most of the Coast Range Mountains south of San Francisco Bay are only 600 to 900 meters in elevation. In the Santa Lucia Range the highest peaks exceed 1,500 meters and in the Tehachapi Mountains at the southern end of the San Joaquin Valley the highest parts attain heights between 1,500 and 1,800 meters above sea level.

The Salinas Valley, having an area of 72,000 hectares and traversed by the Salinas River constitutes the largest agricultural area of this section. The bay-shore valleys south of San Francisco are noted for truck crops, fruits, hay, grain and sugar beets of Salinas and Santa Maria valleys. Adjacent hill lands are used chiefly for grazing and, on the coast side, for the dairy industry. The southern end of this region comprising valley and coastal slopes produces in addition to grazing and dairying, sugar beets and beans, in large quantities. All fruits, except citrus, are grown on a commercial scale. Until recently, the southern part of the section was isolated due to rugged topography and scant rainfall, making the region difficult for making a living in (Coulter, 1930). About one-fourth of the area situated

chiefly in its more rugged isolated part, is unused. The Santa Lucia region consists chiefly of two of the coast ranges, namely the Santa Lucia Mountains and the San Luis Mountains. Several structural valleys in the mountains afford considerable areas of useful land, most of the valleys formed by stream erosion are narrow and steep-sided and many of them are of the canyon type. Soils on the mountain sides are thin. Steep slopes and thin soil make the land mostly suitable for grazing.

The isolation of the Santa Lucia region is emphasized by the character of the coast line and off-shore waters. For 130 kilometers along the northern part of the coast the rugged nature of the shore, many submerged rocks, large beds of kelp, and the prevalence of fogs is a formidable barrier to communication. In recent years a secondary highway has been under construction along the coast from San Luis Obispo to Monterey, by way of San Simeon.

South Pacific:—The South Pacific coast section, comprising an area of 26,000 square kilometers, extends from the southern front of the Santa Ynez Mountains between Santa Barbara and Ventura along the coast to the boundary line between California and Mexico. The San Bernardino Mountains determine the eastern boundary where they rise rather abruptly from the low rolling foothills which in turn constitute the eastern boundary of a very extensive coastal plain sloping rather gently toward the Pacific Ocean.

In this section, including the low hills and the coastal plain, the Los Angeles area, the San Gabriel, and Santa Ana Valleys, away to the mesas and foothills of the high range on the east and narrowing to the south towards San Diego, lies a large and very intensively developed agricultural area. In the central portion of the section lies the metropolitan area of the City of Los Angeles, embracing a population of approximately 1,500,000 and at the extreme southern end of the State, only 20 kilometers from the Mexican boundary, lies the City of San Diego, having a population of about 150,000, and next San Francisco the best natural harbor on the whole California coast.

The mountains in, or bounding on, this section south of the Tehachapi Pass are not so clearly differentiated nor so readily recognized as in middle California. Extending south-eastward from the northern end of the section the San Gabriel, San Bernardino and San Jacinto Mountains group resemble the Sierra Nevada, while the Santa Monica, Santa Susana, Santa Paula and the Santa Ana Mountains are properly regarded as of the coast range type (Waring, 1914). The Santa Ana Mountains, however, merge southward with the outliers of the San Jacinto and Santa Rosa groups to form the Peninsula Range (Fairbanks, 1893), which extends southward to the Mexican boundary and making up the backbone of the Peninsula of Baja California. This range, although lower than the Sierra Nevada, closely resembles it in physiography. San Antonio and San Jacinto peaks are each more than 3,000 meters in elevation, and the highest peak south of the Sierra Nevada, San Gorgonio in the San Bernardino Mountains, attains a height of about 3,500 meters above sea level.

The arable land of this section are intensively cultivated, practically all of it under irrigation. The products are large and various, including most of the present output of citrus fruits, and walnuts, beans in large quantities, sugar beets and truck crops and dairy, poultry, hay, grain and orchard fruits for local consumption. On the uplands dry farming is practiced to some extent and with good results. Since the moist lowlands along the streams are more frosty than the higher slopes they are not well suited to citrus fruits. Here we find alfalfa fields, corn and other vegetables. The vast bean fields, for which Southern California is noted, are found near the coast where the air is damp and foggy. Between the valley lowlands and the steep mountains are the long, gentle slopes, adapted because of soil drainage and climate to the growing of oranges, lemons, figs, olives and grapes. In this almost frostless belt are large areas in orchards and the fruit belt supports most of the towns and cities and exhibits the most intensive culture.

Those interior valleys which are too high and frosty for oranges are usually devoted to grain and temperate fruits, although cattle raising continues to be the leading industry in the less progressive districts. The lower brush-covered canyon slopes support such shrubs as the white sage, noted for the quality of the honey made from its blossoms. In such localities far from common routes of travel we find bee ranches each with its hundreds of hives (Fairbanks, 1921).

The fact that this region was reached and explored from the sea resulted in the first settlements being made near the coast. The first thing taken into account in choosing sites for missions, presidios and ranch buildings was water. The second thing was the question of land suitable for cultivation. The water must be accessible and permanent. Without water for irrigation the necessary food supplies could not be grown.

Sacramento and San Joaquin:—For purposes of this study the Sacramento and San Joaquin sections being quite comparable in physiographical characteristics may be considered together. The sections combined as basin considered embraces an area of 150,000 square kilometers and extends from south of the Siskiyou Mountains in latitude $N41^{\circ}$ about Mount Shasta, in the northern part of California, to the Theachapi Mountains in latitude $N34^{\circ}40'$ on the south, a distance of about 700 kilometers or approximately two-third of the length of California. It lies between the crests of the Klamath Mountains and Coast Range on the west, and the southern Cascade and Sierra Nevada on the east. The inner central part constitutes the Great Valley of California.

From this section lying in the middle of the State and circumscribed by mountains, there is only one sea level outlet through which drains all the waters from the section out into the Pacific Ocean. The Sacramento and San Joaquin valleys are enormous agricultural areas aggregating 5,700,000 hectares extending through the central part of the section, the Great Valley. These plains slope very gently from the enclosing hills at the foot of the mountains and at the same time rise on a very easy gradient toward the upper reaches of the streams.

The foothills at the edge of these plains are low, rolling and largely

agricultural in character and rising in tiers they merge almost imperceptibly into the Sierra Nevada Mountains on the east, and the Coast Ranges on the west. At the lower end where the two valleys merge, lies the Sacramento-San Joaquin Delta area, embracing about 2,000 square kilometers. This delta area, classed as swamps or overflow land, is cut into islands separated by eroded water channels; it is mostly below the elevation of the maximum flood plain and much of it is below the level of extreme low water. About 1,400 square kilometers of the aggregate area have been reclaimed and brought to a very high degree of agricultural productivity by constructing dikes or levees around the individual islands. Rice cultivation is of importance, truck crops and potatoes.

The products of the Great Valley include all grown anywhere in California. The chief grain and hay products of the State have always been produced here, and in recent years it has developed the raisin industry practically all of which is grown in the San Joaquin valley. Alfalfa is grown in large quantities, on which is based the dairy industry. It stands first in the production of shipping and canning fruits grown for drying, except prunes and on the edge of the valley the citrus fruit production is large. The southern extension of the San Joaquin valley produces an increasing cotton crop.

The Sierra Nevada is the dominating physiographic feature on the eastern side of the Great Valley, and one of the most imposing mountain groups of the United States (Whitney, 1865), extending from the southern base of Lassen Peak, in the north, to Tejon Pass, in the south. In the main it forms a great single range which rises in a long gentle slope eastward from the Great Valley to its crest and there descends abruptly to the desert region of the Great Basin at its eastern base. In its northern part this range reaches an elevation of 2,700 to 3,000 meters above sea level. From north to south its elevation increases to its culmination in Mount Whitney, at an elevation of 4,422 meters, thence its height decreases rapidly southward, to Tehachapi Pass.

The eastern slopes of the Coast Ranges form the western portion of this section. In the northern part bordering on the edge of Sacramento Valley, the Coast Ranges attain elevations of 2,000 meters in the Yolla Bolly mountains, lowering southward and reach sea level at San Francisco Bay. The part of the Coast Ranges bordering on the San Joaquin valley floor have an elevation of from 600 to 900 meters, reaching 2,700 meters in Mount Pinos at southern end of the Valley. The Tehachapi Mountains reach elevations of 1,500 to 1,800 meters.

Great Basin:—East of the Sierra Nevada and the southern Cascade Ranges, in California, Nevada and Utah, lies the Great Basin, with an aggregate area of 460,000 square kilometers. The portions within the boundaries of California, consisting of the lava-covered Plateau in the extreme north-east, the south-eastern Desert region and the Salton Sink, formerly known as the Colorado Desert, have an aggregate area of approximately 140,000 square kilometers. These portions differ most markedly from all the rest of California.

The lava-covered Plateau region forms an extensive area in the north-eastern portion of California and most of this area is considered to lie within the Great Basin, although the Pit River and its upper tributaries are draining toward the west, discharging into the Sacramento River and to the Pacific Ocean. The western boundary of the Plateau is formed approximately by the Sacramento River and by Shasta River, a tributary of the Klamath River. Its east and west oriented southern limit lies at the southern base of Lassen Peak; the northern and eastern limits lie beyond the California boundaries in these directions. In the central and northern part this lava plateau lies at an elevation of from 1,200 to 1,500 meters above sea level. In the north-east corner of California the Warner Mountains reach an altitude of 2,400 meters; and westerly lies Mount Shasta, 4,386 meters in elevation. Practically all of this region is covered with lava which is believed to be chiefly of Tertiary and later age. Lake-bed deposits of partially consolidated sands and clays, and areas of alluvium form occasional patches of meadows and valley bottom (Peacock, 1931).

The agricultural possibilities on the Plateau are moderate and have possibilities for development. In the valleys of the Pit River are the larger areas, of which a good portion is under irrigation. The growing season is short and frequent frosts during the spring, and at the higher elevations even during the summer months, occur frequently, forming a limitation to agriculture. Above an elevation of 1,500 meters the lands are used principally for grazing during the summer months. In this region there is a modification of temperature from the north to the south as it is more open to the influence of north and south latitude and is not so fully dominated by local topography and ocean influences, which give to the remainder of California its unique climatic characteristics.

The south-eastern Desert region of California consists of a number of detached mountains and ranges, separated by arid valleys, and by flat areas, of desert alluvium. Saline lakes, playas, and sinks are distributed over large areas. In the northern part the ranges trend in general north and south. The White Mountains in the northern part of this portion have that trend also between Owens Lake and near the Nevada boundary are several roughly parallel ranges with similar direction. In this region lie the Cosa Range, the Argus and the State Ranges, and on the west side of Death Valley the Panamint Range. The Amargosa Range on the eastern side of Death Valley, includes the Grapevine, Funeral and Black Mountains. Farther south are a number of isolated ranges that appear to bear little relation to each other (Waring, 1914). Elevations of 900 to 3,000 meters are reached by most of these mountain masses, the highest of them are in the White Mountains, where Telescope Peak reaches an elevation of 3,369 meters above sea level.

The Salton Sink, an abandoned and dried-out portion of the valley of the Gulf of California, is a large basin, whose sides slope gently to the lowest point, about 80 meters below sea level, in Salton Sea. The Mojave Desert is a broken area with indefinite boundaries lying between the southern end of the Sierra Nevada, the San Bernardino Mountains, and

Colorado River. To the north of Mojave Desert lies Death Valley, and is one of many similar arid valleys in the south-eastern portion of California. It reaches a depth of 85 meters below sea level.

Forests cover 22 per cent of the area of California (Bonner, 1928), the largest and most valuable of which are the redwoods in the North Pacific section between the Klamath Mountains, Coast Ranges and the Pacific Ocean, as well as on the western part of San Francisco Peninsula, north of Monterey Bay. The Klamath Mountains, portions of the lava-covered Plateaus and especially the western slopes of the Sierra Nevada, carry a rich forest cover. Of the total land area of California 403,139 square kilometers, approximately 285,000 square kilometers or about 70 per cent, consists of rough and broken topography, and the remaining 30 per cent, are valleys and plains.

The distribution of the various regions as between flat and mountainous areas may be tabulated roughly as follows:

Table 2.

Region	Valleys or Plains square kilometers	Mount- ainous square kilometers	Total square kilometers
Great Basin (incl. Salton Sink)	41,440	99,102	139,542
San Joaquin Basin	37,037	47,083	84,120
Sacramento Basin	14,763	55,478	70,241
South Pacific (Pt. Conception to Mexico) . .	16,835	11,248	28,083
Central Pacific (Pt. Conception to S. F. Bay) .	3,302	23,947	27,249
San Francisco Bay slope	3,238	5,747	8,985
North Pacific (S. F. Bay to Oregon)	2,072	42,847	44,919
Total for California	118,687	284,451	403,139
	29.4 %	70.6 %	100.0 %

III. Outline of Geology.

Voluminous records of the geologic history of California and of the whole Pacific Coast are to be found in the numerous and thick sediments of these regions. While scanty and incomplete for the pre-Cambrian periods, those antedating the appearance of life on the earth, or at least containing no evidence of the living organisms that existed from the Cambrian period on for these latter eras the region presents as a whole a volume and richness of detail that is seldom equalled. Beginning with the Cambrian and extending down to the present time each period is represented by marine deposits which register the geography, climate and something of life that existed at the times the deposits were laid down. Earth movements and volcanic activity is recorded not only in the character and distribution of the igneous rocks but also in the metamorphism and mechanical deformation of the sedimentary rocks of the region. This latter record imprinted by metamorphic processes often eradicates the earlier records of the sea. The history of the relatively recent periods is written and preserved in as great

detail as in other regions of the world. Marine, terrestrial and glacial conditions, of the peneplaining of mountain ranges, followed by earth movements and volcanism, and the re-birth of mountain systems, contribute to the text of the geologic history of the region.

Formations of proved pre-Cambrian age doubtless exist in California but only in patches and the proof of the suspected antiquity of these strata is lacking. East from California and the Pacific Coast intense and regional metamorphism is generally considered proof of great geological age. In California and the Coast region such changes in the rocks merely indicate an age antedating the intrusion of the Sierra batholith. Patches of known pre-Cambrian occur north-west of Owens Lake (Reed, 1933), where a metamorphosed series appear underneath strata carrying lower Cambrian fauna, *Olenellus*; areas of probable pre-Cambrian are found in the Desert Mountain ranges bordering upon Arizona, and that proved pre-Cambrian occurs in the Grand Canyon of the Colorado River and adjacent areas, has long been known. Certain ancient schists in the Siskiyou Mountains of Northern California have been provisionally assigned to this period (Tolman, 1915). It is also believed that older gneisses and schists of the San Gabriel, San Bernardino and San Jacinto mountain ranges in southern California are of pre-Cambrian age but this has not yet been proved.

All other components of these ranges are of latter age, including Palaeozoic formations, chiefly quartzites and limestone, granitic intrusions of post-Palaeozoic age, contemporaneous with, or possibly somewhat later than the batholith of the Sierra Nevada, and also still younger, deformed, but metamorphosed strata. The granitic masses of the southern California ranges, the Sierra Madre, San Jacinto and San Bernardino are now generally considered as outlying members of the greatest granitic mass, the Sierra batholith. Consequently, there are few data from which to reconstruct the Pacific Coast region preceding the great Palaeozoic invasion of the sea.

It is known, in general, that the American continent was elevated above the sea probably far beyond its present boundaries, and was gradually reduced in level. Early Cambrian time overspread Nevada with an extension of the Great Basin onto adjoining areas including California, while the region now occupied by the Sierra Nevada Mountains was filled with a low land mass, an island, or perhaps an archipelago, in the south-eastern section. During the Palaeozoic age the Great Basin continued to advance intermittently, until at the close of that era it may have reached as far west as the present coast line in the vicinity of Monterey. The Pacific Ocean lay to the west of the present coast line, a condition which probably existed through Palaeozoic, Triassic and Jurassic times. The total thickness of this series of coastal deposits is according to Tolman at least 3,000 meters in California and consisting largely of metamorphosed shales and sandstones, and in the Devonian and Carboniferous periods extensive deposits of limestone, interstratified with large amounts of lavas and tuffs.

The Triassic and Jurassic sediments were laid down in a relatively small inland sea or sound, extending over only the northern portion of California occupied by the former Great Basin Sea. This sea which formerly extended

over a large portion of California had now diminished to a much smaller water body probably connected with the Pacific Ocean but separated from it by a great island including the western portion of California and Oregon, and probably extending considerably west of the present coast line. The maximum thickness of the marine Triassic and Jurassic of north-western California reaches or exceeds 2,400 meters. This suggests that there was a nearby land mass, although no mountain ranges were in existence as yet.

The oldest rock formation that has so far been exposed along much of the present Coast Range, and which underlies the City of San Francisco, is a thick and widespread series of rocks known as the Franciscan series, comprising sandstones, conglomerates, shales and local masses of variegated, thin-bedded, flinty rocks and carrying occasional intrusions of diabase, peridotites and serpentine, the latter associated with glaucophane, forming schists that is one of the outstanding characteristics of the Franciscan series. In spite of wide distribution and easy access, great difficulties have been encountered in determining the age of the Franciscan rocks, geologists, not being in accord on this question, assign it variously to the late Jurassic and early Cretaceous. Few fossils have been found except tests of radiolaria and foraminifera, furnishing little reliable data for geologic correlation (Tolman, 1915). Close folding and the frequent occurrence of double soil cover are hindrances to structural studies. The Franciscan series have at one locality, Corral Hollow, south of San Francisco, been measured to 4,500 meters without exposing either top or bottom. The position of the Franciscan under the Knoxville series of early Cretaceous age, suggests a pre-Cretaceous age. A portion of the series lies unconformably on granite, and if this granite is contemporaneous with the last of the granites of the Sierra Nevada, a post-Jurassic age is indicated.

It seems certain, according to most geologists who have studied the region, that before the rise of the Sierra Nevada, an important trough west of it existed, and in which sedimentation was active. On the east side of this trough the Mariposa formation of Jurassic slates was deposited, while on the west side of the trough the Franciscan series were formed. This trough was probably post-Palaeozoic and pre-Cretaceous in age. To the west the more important types of marine life were rare, but large amounts of organic siliceous ooze were deposited. The land mass from which the terrigenous sediments were derived may have existed to the west of the present coast line.

The Cordilleran Revolution:—The rise of the Sierra Nevada and intrusion of the batholith, a single solid mass, took place in late Jurassic times. The main batholith occupies the central eastern portion of California, forming a large inclined block 750 kilometers in length by a width about 125 kilometers running in a direction a little west of north. The western slope is very gentle while the eastern descent to the desert floor of the Great Basin in Nevada is very abrupt. This abrupt descent marks a line of faults, east of which the desert country has subsided, and the west of which has been uplifted. At the northern end near Lassen Peak it disappears under the lava cover of the Cascade Range of California and Oregon. In this

region small granitic masses may be outliers of the same great intrusion. Towards the south, the block curves into a hook, encircling the Great Valley of California.

The batholith consists of a great irregular mass of granite which has been intruded in a molten condition into sedimentary and older igneous rocks, which in consequence of the heat and pressure incident to this intrusion were changed in part to schists and slates. The metamorphism accompanying the intrusion was so intense and widespread that it resembles regional rather than contact action. As a result much of the Cretaceous rocks appear as schists, slates and recrystallized limestones.

The irregular masses of the Sierra Madre, San Jacinto and San Bernardino ranges of southern California, as well as the smaller granite areas of the southern Coast Ranges, may be closely related to the main batholith. The small granitic masses of the desert region of south-eastern California belong to the Great Basin Province, and a close relationship to the Sierra Nevada batholith has not been proved.

Sills and dikes of serpentine were intruded along the axes of the present Coast Ranges. These may have been contemporaneous in part with the later phases of the batholithic intrusions of Sierra Nevada, which also include basic derivatives. The intrusion of the Coast Range serpentine continued, however, into early Cretaceous times.

"Prior to the intrusion of the Sierra Nevada granites, the earth movements which brought about the Cordilleran revolution were well under way . . . The Coast Ranges of California received their first and greatest folding at this time" (Lawson, 1894). The Franciscan series is pressed into a regular system of folds, which often consists of open synclines and broken, compressed anticlines, but locally of isoclinal structure. The folds of the Coast Ranges are cut diagonally by the present coast line, the system disappearing under the ocean near the boundary between California and Oregon. The Cordilleran revolution impressed upon the west coast region, its present structural pattern and outlined the positive (rising) and negative (sinking) elements which persist today (Tolman, 1915). That main negative element is the great central trough extending from Puget Sound to the Gulf of Mexico. The positive elements are the highlands and mountain ranges on either side of the trough. In California especially, the folded zones initiated during the late Jurassic periods have governed subsequent deformation. The great faults, for the most part of subsequent origin, show a general parallelism to the trend of the folds.

The Klamath Mountains which may be considered as a mountain knot connecting the Coast Ranges with the Sierra Nevada-Cascade system, belong structurally with the folded complex of the latter range. During the Cordilleran a complete readjustment of the distribution of land and water took place, the Pacific Ocean advancing eastward (Diller, 1902), while the Great Basin Sea was laid dry and from now on we have to do with the advances and retreats of the epicontinental respectively the Pacific Ocean. The whole territory represented by the Shasta-Chico beds (Lower and Upper Cretaceous) gradually subsided as the sea advanced, sweeping across the

north end of the Sierra Nevada through the Sisson Strait, where today Lassen Peak stands. The recently folded Coast Ranges stood but a brief interval of time above the ocean, which also crossed the site of the present Cascade Range, in southern Oregon.

The early Cretaceous (the Shastan) was marked by a rapid advance of the Pacific Ocean over the western portion of the Pacific States and more than 6,000 meters of sediment, the Shasta-Chico series, accumulated in the Sacramento valley. The Chico sediments register a second great advance of the Pacific Ocean which covered the abraded Klamath Mountains and reaching the foothills of the Sierra Nevada. During the Eocene period northern California and a large portion of Oregon were above the sea and were subjected to degradation. At some localities along the coast local Eocene basins were converted into swamps for brief intervals of time, the organic accumulations of which are preserved as lignite. The Miocene period of California was marked by the deposit of diatomaceous material which is one of the chief sources of the California oil. Miocene deposits are in California laid down to great thickness, and this period, which is considered to have been of relatively short duration, also embraces an orogenic period of no small dimensions. Middle Miocene is the date generally assigned for the second folding of the Coast Ranges coinciding with partial elevation of the region. However, local but pronounced folding occurred in the late Miocene and early Pliocene east of San Francisco Bay. In the vicinity of San Francisco Bay, thick lacustrine deposits of upper Miocene and lower Pliocene age appear. From Miocene times onward the section east of the great central valley, from northern California through Oregon and Washington underwent vast volcanic eruptions which covered an area exceeding 500,000 square kilometers, forming a huge plateau of lava of from 900 to 1,500 meters in depth. It is sentinelled on the west by lofty volcanoes, such as Mount Shasta, Mount Hood, Lassen Peak, Mount Ranier, Mount Adams and many others.

In south-eastern California, a terrestrial and lacustrine deposition took place throughout all of Tertiary and Quaternary periods. In the Quaternary period mountain glaciers occupied the higher portions of the Sierra Nevada and remnants of which are preserved as the small mountain glaciers of today.

The dynamic history of this region since Jurassic times is varied and complicated. During the Cretaceous, the Sierra Nevada-Cascade ranges were eroded so that at the close of the period portions were reduced to an approximate base level as in the Klamath Mountains (Diller, 1902). In the Sierra Nevada, base leveling was delayed by elevation of the mountain range which may be considered broadly as a great fault block, with an important zone of faulting on the east side. The movements tilted the block gently toward the west and elevated it above the desert region of Nevada (Lindgren, 1911).

While there occurred many elevations of this region during the Tertiary period, erosion at that time gained the upper hand, and the Sierra Nevada was reduced in part to a peneplain. In the late Tertiary and Quaternary

times uplifts culminating in great elevations during the Quaternary period, produced the Sierra Nevada as we see it today, through a maximum upheaval of perhaps more than 2,000 meters, at the same time as a fault of some thousand meters developed along the eastern slope of the range. The erosion is as yet in a very youthful stage and except for the tilting, this great mountain block has acted as a resistant buttress and has not suffered the intense deformation that affected the weaker regions in the Great Basin as well as in the Coast Ranges in Tertiary and Quaternary times.

The Sierra Nevada has been planned down to a surface of comparatively gentle topography. (Lindgren, 1911), claims that it must originally have been of great height. Traces of this eroded range (Cretaceous) "still remain in a number of flattopped hills and ridges that rise above the later tertiary surface. There is reason to believe that this planned-down mountain range had a symmetrical structure, for somewhat to the east of the present divide is a well-marked old crest line extending from the Grizzly Peak Mountains on the north, in Plumas County, at least as far south as Pyramid Peak in Eldorado County. At sometime in the later part of the Cretaceous period the first breaks took place, changing the structure of the range from symmetrical to monoclinical and outlining the present form of the Sierra Nevada."

This great disturbance was of two-fold character, consisting of the lifting up of a large area including at least a part of the present Great Basin and a simultaneous breaking and settling of the higher portions of the arch. Along the eastern margin a system of fracture was thus outlined which toward the close of the Tertiary was to be still further emphasized. The main break probably extended from a point south of Mono Lake to Antelope Valley and from Markleville northward toward Sierra Valley. A large part of the crust block to the west of this dislocation also sank down. This sunken area is now indicated by Lake Tahoe, 22 miles long, and by its northward continuation, Sierra Valley, separated from each other only by masses of Tertiary lavas. It is worthy of note that within the area of the range no volcanic eruptions accompanied this subsidence.

As a consequence of this uplift the erosive power of the streams was rejuvenated, the Cretaceous surface of gentle outline was dissected, and the rivers began to cut back behind the old divide carrying their heads nearly to the present crest line that separates the slope of the Sierra Nevada from the depression of Lake Tahoe. These rivers are the gold bearing streams of California. They all head in the Lake Tahoe region, and include the Yuba, Feather, American, Mokelumne, Calaveras, Stanislaus and Tuolumne.

Lindgren points out that there were two crest lines, the old Cretaceous line of which the Crystal Range immediately overlooking Desolation Valley on the west, with Pyramid Peak and Agassiz Peaks as its salient features, and the new Tertiary crest line reaching somewhat irregularly from Honey Lake in the north to Mono Lake in the south. At the north end of Lake Tahoe to Sierra Valley enormous andesitic eruptions took place and the products of these volcanoes are now piled up as high mountains, among which Mount Pluto, nearly attains 2,700 meters in elevation.

While the Mount Pluto was being formed other vast volcanic outpourings were taking place. Well back to the west from Lake Tahoe region volcanoes poured out rhyolite and on the summit nearer to the Lake the volcanic outflows were andesite. By far the greater part of the andesite occurs in the form of a tuffaceous breccia in numerous superimposed flows. These must have issued from fissures near the summit of the range and were mixed with large volumes of water forming mud flows sufficiently fluid to spread down the slope for a distance of 80 to 95 kilometers. Another volcanic complex with many eruptive vents is that situated in the western part of Alpine County farther to the south, near Markleville, which culminates in Highland Peak and Raymond Peak, the former almost reaching 3,300 meters. The total thickness of the volcanic flow in this locality is as much as 1,200 meters. "None of the craters," says Lindgren, "of these volcanoes are preserved, and at the time of their greatest activity they may have reached a height of several thousand feet above the present summits."

The early tertiary history of the Cascade Ranges is largely buried under the great lava cover. Their southern portions owe their present height to upbuilding processes, great volcanic cones dominating the range. The Klamath Mountains received the full thrust of later compressive movements intensified possibly by the resistance offered by the unyielding Sierra Nevada block. The boundary between the Coast Ranges and the Klamath Mountains is marked by a great overthrust along which crystalline schists have overridden the Jurassic and Cretaceous rocks to the west.

Throughout the Tertiary compressive stresses accumulated along the Coast Ranges, local relief or crumpling taking place, the most pronounced folding occurring in the middle Miocene. Great faults developed in general parallel to the trend of major folds. The fault movements appear to have reached a maximum during the uplift of the entire west coast region in Quaternary and recent times.

The elevated beach lines show that recent elevations of the coast have been important (Diller, 1902), also local downwarps have taken place as at the mouth of the Sacramento River, forming San Francisco Bay, San Pablo and Suisun Bay (Lawson, 1893 and later), and isolated Santa Catalina and other islands from the mainland of southern California.

IV. Climatology.

The most distinctive meteorological feature of California is perhaps the ordering of its seasons of which it has practically but two that are well defined, winter and summer, or wet and dry. This occurs because the transitional periods, spring and autumn, are brief and devoid of special features other than that they are intermediary between the more clearly defined seasons, summer and winter. The summer or growing period, is long, warm and without heavy rains; the winter is the dormant period, or interval of retarded growth in the annual cycle of plant life, and is normally

short, cool, and at times stormy. Most of the annual precipitation occurs during the season of winter.

The climate in California as a whole, is such that during a twelve month period, not conforming to the calendar year, there are but two fairly distinct although not so sharply marked seasons. The winter, or wet period, is approximately from October to March, and the summer, or dry season, covers the balance of the twelve-month period, or from April to September inclusive. Variations in beginning and end of the rainy season from one twelve-month period to another is as large or larger than the variation of beginning and end of the rainy season from south to north, a distance of nine and one-half degrees of latitude. Temperature range, both seasonal and locational, is far from uniform over California as a whole, and even within the individual physiographic sections or individual drainage basins, there is material variation.

The mountains and the proximity of the Pacific Ocean upon which California borders with a 1,500 or more kilometers long coast line, so modify the climate that only moderate seasonal fluctuations of temperature over most of the area of California take place. Any great extremes of heat and cold that do occur are confined principally to the non-agricultural high mountain areas or to the arid portions. For California generally, the mean summer temperature and mean for the winter show a less departure from that of the entire yearly temperature than do similarly compared mean heat for the adjoining states, or those located eastward and included in the same latitude.

The seasonal fluctuations of temperature, the duration of periods of heat and cold, and the extremes of temperature reached in the daily and yearly cycle all have an effect on vegetation. Agricultural plants require appreciable intervals of favorable growing temperature that they may attain to mature growth and reach an annual harvest bearing stage. This growing period must necessarily be continuous and for the greater number of agricultural plants the growing season must be free from freezing temperature or long continued chilling cold.

Although all California shares the seasonal peculiarity of its climate, the northern and southern, roughly dividing at Point Conception and the Tehachapi Range, are very unlike meteorologically. The northern portion is relatively humid with more than twice the average rainfall of the southern portion, with far less streams and vastly richer forestation. At Crescent City, on the north coast, precipitation often reaches 2,500 millimeters per year. The trend of the coast is here northerly, and the region shares something of the extraordinary humidity of the coast of Oregon. The smallest precipitation in the State is to be found in the arid south-east corner averaging only 75 millimeters per year at Yuma on the Mexican border and Colorado River. The southern portion of California has an average annual rainfall of about 375 millimeters. This broad difference between the two geographic portions in precipitation has been the chief factor in an extraordinary difference of development since the beginning of the century.

The Salton Sink formerly called the Colorado Desert is the hottest part of the United States. Along the Southern Pacific Railroad the yearly extreme is frequently from 51° to 54° C in the shade. At the other extreme temperatures of -20° to -38° C, are recorded yearly near Lake Tahoe. The normal annual means of the coldest localities of California are from 2.8° to 6.7° C; the monthly means from -6.7° to 18.3° C; the normal annual means on Indio, Mammoth Tanks, Salton and Volcano Springs are from 23° to 26° C; the monthly means from 11.5° to 38.5° C; frequently 35° to 36.7° C. For continued heat and aridity the Death Valley surpasses the Salton Sink.

Another weather factor is the winds, which are extremely regular in their movements (McAdie, 1915). There are brisk diurnal sea breezes, and seasonal trades and counter trades. Along the coast an onshore breeze blows every summer day; in the evening it is replaced by a nightfog, and the cooler air draws down the mountain sides in opposition to its movement during the day.

Along the entire Pacific Coast, but particularly north of San Francisco, there is a night fog from May to September and even during the winter months there is fog, very noticeable around the Golden Gate region. The extreme heat of the south-east is tempered by the extremely low humidity characteristic of the Great Basin. Many places in very different geographical location in California normally have 200 days or more of clear weather a year, in the high mountains and in the south, even on the coast there are more than 250 clear days per year.

Climatological data has been collected during varying periods of time at fairly well distributed record stations. Rainfall stations at present time are about 800. The seasonal temperature range in the coast area is moderate. In the North Pacific section "highs" are considerably lower than in the South Pacific section, while the "lows" in the South Pacific section are generally considerably higher than those occurring in the North Pacific section. Generally, the range in the San Francisco Bay section lies between these two extremes and in the Central section, the range is somewhat greater than in the San Francisco Bay section. Along the coastal area, however, no long periods of continued high or continued low temperatures occur. In the winter, freezing temperatures do occasionally occur; in the summer, temperatures in excess of 30° C seldom occur in the North Pacific section, and in the San Francisco Bay section; while in the South Pacific section temperatures up to 32° or 35° C occur occasionally. In the Sacramento and San Joaquin sections the annual range of temperature is considerably greater than that in the central area, particularly as regards the summer "highs" on the valley floor. Temperatures as high as 43° and 45° C are not uncommon during the summer, while freezing temperatures do occur during the winter. In the mountain area, surrounding those valleys, winter temperatures materially below freezing do occur, particularly in the Sierra Nevada Range, but summer temperatures in excess of 21° to 27° C are very unusual. The Great Basin, including the lava-covered Plateau, being in large part desert (Steppe), in character, are subject to temperature ranges

characteristic of such areas, very hot during most of the summer months and extremely cold during the winter period.

Comparative physiographic section temperatures giving the principal values of two localities in each section follows:

Table 3.

Section	Station	Yrs. Record	Eleva- tions Meters	Mean Temperatures			Max. Sum- mer Temp.	Min. Winter Temp.
				Nov. 1- Mar. 31	Apr. 1- Oct. 31	Annual		
North Pacific	Santa Rosa	45	51	9.9	16.6	13.6	44.4	— 9.4
	Yreka	30	800	3.5	15.8	10.9	42.8	—21.7
San Francisco	San Jose	60	29	10.3	16.2	14.2	42.2	— 7.8
Bay	Oakland	58	98	10.6	15.7	13.6	41.1	— 3.9
Central	Hollister	60	86	10.6	17.0	14.4	44.4	— 7.2
Pacific	Paso Robles	47	244	9.4	18.3	14.2	45.0	—10.6
South	Los Angeles	52	103	13.9	19.0	16.9	42.8	— 2.2
Pacific	San Bernardino	42	308	12.5	20.6	16.4	46.7	— 7.8
Sacramento	Sacramento	81	21	10.0	19.4	16.6	43.3	— 8.3
Basin	Soda Springs	60	2059	— 0.6	15.6	4.7	32.2	—33.3
San Joaquin	Fresno	46	100	10.3	22.2	17.5	46.1	— 7.8
Basin	Huntington L.	18	2135	0.6	10.6	6.4	31.7	—24.4
Great	Tahoe	24	1900	— 0.7	10.2	5.6	34.4	—26.1
Basin	Barstow	13	642			17.9	45.6	11.1

Summer temperatures in the interior valleys are higher than those found nearer the Pacific Ocean as the 1,500 kilometers or more of coast line of California modifies the coastal climate to an equable temperature freer from the extremes of heat found farther inland. Use of water by plants, disposed of by transpiration, is affected by numerous factors of which temperature is one of the most important. Crops grown in the coastal areas require less water than those grown in the interior.

The frost-free period in the agricultural districts is generally long in comparison with those of other parts of the West. Snowfall is abundant in the mountain districts, providing storage for summer stream flow, but is of rare occurrence in the lower valleys of California. Evaporation in summer is higher in the interior than along the coast and because of the long period of warm weather the total loss of moisture by this means is considerable.

V. Precipitation.

Precipitation is a more vital factor in a region which depends upon the produce of the soil, than it is in a manufacturing district. For this reason the question of rainfall in California is very closely bound up with its economic stability, not only because of its direct influence upon irrigation and public water supply, but indirectly through its connection with hydro-electric power and the agricultural and industrial development dependent thereon.

Precipitation data in California attain the importance of vital statistics. The water problem in California, as in most States lying west of the Mississippi River is all-important. The East has no water problem comparable in magnitude with that of the West, and probably in no other region does the public watch the rainfall statistics as closely as in California. It has always been so, apparently. Ever since the discovery of gold there have been large areas and much property menaced by the floods resulting from occasional excessive rainfall. The water runoff brought life to the mining camps in the early history of gold mining in California, where the placer soil and gravel of the diggings were washed from the gold by its aid. Plenty of water meant plenty of gold to the miners and to the State in those early days of '49.

Today the irrigator and the hydroelectric power producer and the cities which draw upon surface sources are all interested. Will the season be wet or dry is the annual question as winter approaches and in the middle of it, at the moment of writing, as we are 70 millimeters behind in the seasonal quota (Feb. 25). What is more natural, therefore, than to find the public generally given to prognosticating and interpreting signs. They study the moon to see whether it is a wet or dry moon, they base predictions upon the early or late flight of the geese from the northern regions, or upon the summer temperature, or they will even venture predictions on sunspots or on the six months earlier climate in Europe. In the meantime the meteorologist can do not much better than the practical man, for he must content himself with the determinations of probabilities on the basis of records which disclose the weather conditions of the past.

The average annual precipitations in California ranges from 37 millimeters at the Greenland Ranch, Inyo County, in the Great Basin, 570 millimeters at San Francisco, 2,000 millimeters in the Sierra Nevada north-west of Lake Tahoe to 2,780 millimeters at Monumental, Del Norte County, in the north-west corner of the State near the Oregon boundary. The southern California Coastal Plain receives at various locations averages of from 380 to 500 millimeters. Within the California boundaries are also included the region of near-greatest snowfall in the United States; and regions in which snow of measurable amount has never been known to fall. There is a general increase in average precipitation from the south-east to the north-west, moreover the mountains are regions of heavy precipitation while in the interior basin regions and the southern plateau region precipitation is deficient. Records give evidence that there is an increase in average annual precipitation up to an elevation of 1,500 meters in the central Sierra Nevada, and a decrease above that altitude. While there are many exceptions the rate of increase up to 1,500 meters in elevation is about 70 millimeter per annum for every 100 meters increase in elevation.

This is an average value for the Sierra Nevada. The increase, however, is not uniform from the foot of the Sierra Nevada to the top but is lower at lower elevations than at greater height up to the before mentioned elevations of 1,500 meters. This fact has been known to be true for other mountainous regions (Krebs, 1890, 1908), (Lee, 1911).



Bucks Creek Power Plant, North Fork Feather River, northern Sierra Nevada. Static Head 780.1 m from Elevation 1,316.4 to 536.3 m above sea level. Installation 40,000 Kw. Highest head plant constructed in California. Completed 1928.

Courtesy Pacific Gas and Electric Company, San Francisco, California.

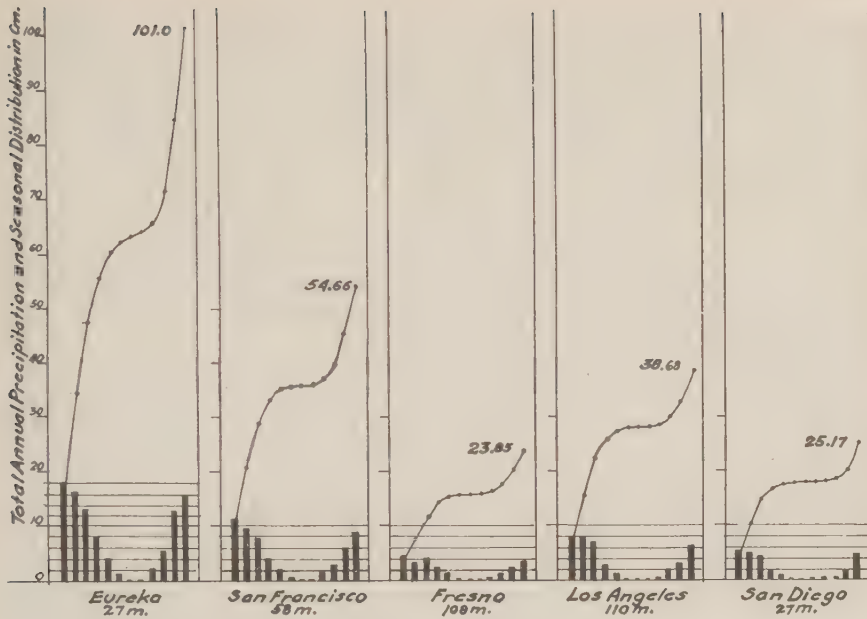


Fig. 2. Normal Precipitation at Five Recording Stations.

There is a general tendency toward greater precipitation in the higher mountain regions where a depth of more than 1,800 millimeters is reached near the northern summits of the Coast range. The elevated peaks and tablelands of the western slope of the Sierra Nevada Mountains receive a mean precipitation of 1,250 to 2,300 millimeters compared to depths of from 125 to 635 millimeters occurring in the Great Valley between the two ranges. The rainfall over the extensive and continuous areas of agricultural land in the San Joaquin and Sacramento valleys, is less in depth and more uniform than over the mountainous areas.

While the precipitation varies from 37 to 2,780 millimeters in depth over the state, the Great Valley in the center of the state, containing the bulk of California's agricultural land receives 380 to 635 millimeters in the north half and the south half receives only 125 to 380 millimeters. South of Tehachapi Pass the southern California coastal valleys, lying to the west of the dividing range, have a rainfall of from 225 to 380 millimeters of rainfall a year. On the eastern side of this mountain range dividing the coastal plains from the desert, lies a great expanse of territory, one-fifth of the total area of the State, which receives less than 125 millimeters of rainfall per annum. To the north and along the eastern border of California, the mountain valleys lying east of the Sierra Nevada and south of Lake Tahoe, have a mean precipitation of from 125 to 635 millimeters; those north of Lake Tahoe and on the mountain plateaus east of Mount Shasta, receive from 250 to 500 millimeters per year. Along the western border

of the State, on the Pacific slope of the Coast Range Mountains, the agricultural valleys north of Cape Mendocino and west of Mount Shasta, have a precipitation of from 500 to 1,900 millimeters; the valleys from Cape Mendocino to San Francisco Bay receive from 500 to 1,250 millimeters per year. The valleys on this same slope, between San Francisco Bay and Santa Barbara Channel, have a rainfall that varies in depth from 250 to 635 millimeters per annum.

The annual precipitation on all these areas varies greatly from year to year. Long continued records of rainfall give, when averaged, a mean depth of annual precipitation which shows the quantity of water that should be expected to fall in any one year; but the precipitation actually occurring departs widely from the average computed.

Precipitation is unequally distributed in California, as noted above. The ultimate source of practically all the precipitation in California is the Pacific Ocean. As the moisture is brought in by the westerly winds, the eastern and north-eastern slopes of the south-east—north-west oriented mountains receive much less precipitation than the western and south-eastern slopes. The precipitation is unequally distributed throughout the year, winter being the wet season and summer the dry season. Toward the north the distribution of rainfall throughout the year becomes more nearly equalized. In southern California about 90 per cent of the annual precipitation occurs during the winter half-year, while in northern California the proportion is about 75 per cent.

The heaviest recorded precipitation for a calendar year in California is 4,000 millimeters, which occurred in 1911 at La Porte, Plumas County, in 1,500 meters altitude. Nearly every year at one or more stations precipitation of 2,500 millimeters and over has been recorded. As the greater part of the annual precipitation is recorded during six months, extraordinary amounts fall within short periods of time. The greatest recorded by the United States Weather Bureau in one month is 1,800 millimeters, which fell during January, 1909 at Helen Mine, Lake County, in the Coast Ranges north of San Francisco, altitude 839 meters. The greatest amount recorded in 24 hours is 424 millimeters, which fell January 16—17, 1916 at Squirrel Inn, San Bernardino County, southern California, altitude 1,610 meters. At Campo, San Diego County, altitude 776 meters, 292 millimeters of rain fell in one hour and twenty minutes, on August 12, 1891 (Palmer, 1920).

In contrast, consider the record of Bagdad, San Bernardino County, altitude 239 meters, where no measurable rainfall fell from October 3, 1912 to November 8, 1914, inclusive, a period of more than two years. At Indio, Riverside County 6 meters below sea level, no measurable rainfall fell from November 1893 to January 1895, a period of more than one year. At several stations in the Imperial Valley and at one in Death Valley, both of which depressions are below sea level, there have been periods of a year or more in which not more than 25 millimeters of rain fell.

Snowfall is of greatest importance to California. Since most of the precipitation comes during the winter season, the elevated portions of the State have abundant snowfall. Tamarack, Alpine County, south-east of Lake

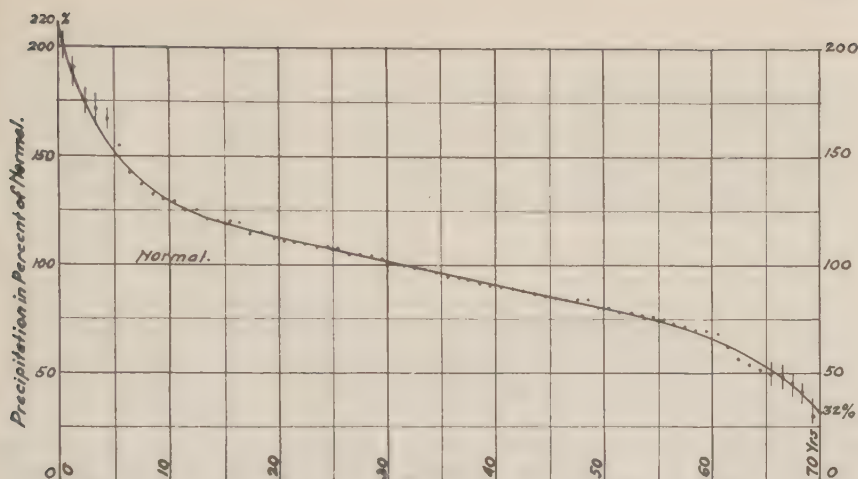


Fig. 3. Departure of the Precipitation from the Normal in 70 Seasonal Years Based on the Combined Records at San Francisco and Sacramento.

Tahoe, altitude 2,400 meters, has an average winter snowfall of 13.25 meters based upon a record of eight years. Nearly all the stations in the higher portions of the Sierra Nevada Mountains receive more than 2.50 meters of snow every winter. The greatest amount recorded during one winter is 22.50 meters, which fell at Tamarack during the winter of 1907-8. From 12 to 15 meters of snow has been known to accumulate on the ground at one time in the high Sierra Nevada. The importance of this snowfall has been pointed out (Ward, 1917). He says: "The Sierra Nevada Mountains well deserve their name. To them California owes much, if not most, of her present prosperity and her promise for future growth and development. The many feet of winter snowfall which accumulate on the upper slopes mean millions upon millions of dollars each year to the farmers and fruit growers of southern California. Were all this precipitation to fall as rain, every winter would witness devastating floods, and every summer would wither and destroy the crops."

The following list of crest snow survey stations along the Sierra Nevada with the normal water content of the snow cover at each, on April 1, show the enormous quantities of water stored up over the mountain surface at the time of the year when draft for irrigation is about to begin:

Table 4.

Basins	Elevation Meters	Water Content Millimeters
Upper San Joaquin-Owens at Mammoth Pass .	2,900	1,186
Tuolumne-Mono at Dana Meadows	2,960	869
Tuolumne-Walker at Sonora Pass	2,840	1,102
Stanislaus-Walker at Sonora Pass	2,680	737

Basins	Elevation Meters	Water Content Millimeters
Mokelumne-Carson at Blue Lakes	2,440	1,085
American-Tahoe at Lake Lucile	2,565	1,689
American-Tahoe at Rubicon Peak	2,470	1,270
American-Tahoe at Ward Creek	2,135	1,240
Yuba-Truckee at Summit Station	2,187	1,031
Yuba-Truckee at Webber Creek	2,440	1,185
Lassen Peak (1932)	2,565	1,288

The rainfall records which are available in California are exceptionally good (Grunsky, 1920). The importance of the rain and snow as an economic factor was recognized by the early settler, with the result that good records were kept, so that the character of the seasons since 1849 in the matter of rainfall is fairly well known for all California. The concentration of most of the precipitation into a winter period of six months with wide departures from the mean, lent a peculiar fascination to the collection of these data which now facilitate comparisons and which have aided in no small degree in determining local limitations upon dry farming, farming by irrigation and more recently the limitations upon hydroelectric power output. The records kept by many reliable individual observers beginning in 1849 and later, have been preserved and later rendered an invaluable service not only to meteorologists but to agricultural investigators and to practicing hydraulic engineers. With the aid of these records to supplement the more recent United States Weather Bureau records, and with others somewhat less complete and dependable, and with many more or less fragmentary records scattered throughout California, it has been possible to determine with some approach to the truth what the normal or mean annual rainfall is in practically all portions and it has also been made possible to give for almost any locality a fairly dependable approximation of the precipitation in any seasonal year. The term seasonal year is used to express the twelve months beginning with July and ending with June. The distinction between rainfall in a calendar year and in the seasonal year is very important for the Pacific Coast region because the six months during which nearly all of the season's rain falls represent a period which overlaps from one calendar year into the next. It would be meaningless in California, therefore, to compare the rainfall of calendar years with each other. In California it has become universal custom to note the rainfall for the seasonal year. It is this precipitation which must be given credit for the season's runoff and all that this may mean in the matter of floods, and irrigation and hydroelectric power output.

Precipitation records are, as we have seen, fairly well distributed over California and have been maintained for longer or shorter periods. An adequate conception of the wide annual range as between the various sections will be had from the following recapitulation, considering each of them:

North Pacific:—In this section precipitation averaging more than 1,000 millimeters of rainfall per season and ranging from 250 to 2,500 millimeters

as of different seasons, is ample for all agricultural purposes to which this section is suited, with the possible exceptions of those areas in the northern portions of the section in which irrigation is practiced to a limited extent.

San Francisco Bay:—In this section, annual precipitation averaging from 710 to 760 millimeters of rainfall per season is ample for all agricultural purposes, although to a limited extent, irrigation is practiced in some parts of the section.

Central Pacific:—In this section precipitation averaging from 250 to 500 millimeters of rainfall per season is such as to rather definitely classify this area as semi-arid in character.

South Pacific:—In this section, precipitation averaging 250 to 380 millimeters of rainfall per season very distinctly classifies this area as semi-arid.

Sacramento and San Joaquin:—In the mountains surrounding the Sacramento and San Joaquin sections, precipitation ranges from 760 millimeters of rainfall in the Coast Ranges to 6 meters of snowfall or more in the Sierra Nevada Mountains; while on the valley floor the annual rainfall seldom exceeds 250 to 380 millimeters, and definitely classifies as semi-arid this large agricultural area.

Great Basin:—The portion of this section lying within the boundaries of California is with the exception for some valleys in the north chiefly non-agricultural in character and consists largely of desert waste and barren hills. Annual precipitation is very small.

VI. Evaporation.

The main conception underlying recent studies is that evaporation is controlled by the energy which becomes available for that purpose. Energy is supplied to a water body by the sun and is discharged by evaporation and back radiation. Furthermore, the air over the water may either contribute heat or carry it away according to the direction of the temperature difference. Also since the heat capacity of a water body is large great quantities of heat may be absorbed thus decreasing for a time the amount available for evaporation. Or the water may cool and thus increase the heat available for evaporation while the cooling is going on.

The controlling factor, far outweighing any other factor, which influences the rate of evaporation from an open body of water, is temperature, and particularly, the temperature of the water at the surface. The effect of wind and of humidity of the air upon the rate of evaporation are secondary. The climatological conditions, to be sure, have an influence upon the evaporation. Consequently the depth of water evaporated annually from inland bodies of water varies widely in different sections. In some measure the water temperature of the water surface of a lake or reservoir will follow or will change with the temperature of the air, provided that a considerable period of time is taken into account. Various formulas have been proposed for calculating the depths of evaporation, factors being introduced to allow for changes in temperature, wind velocity, relative hum-

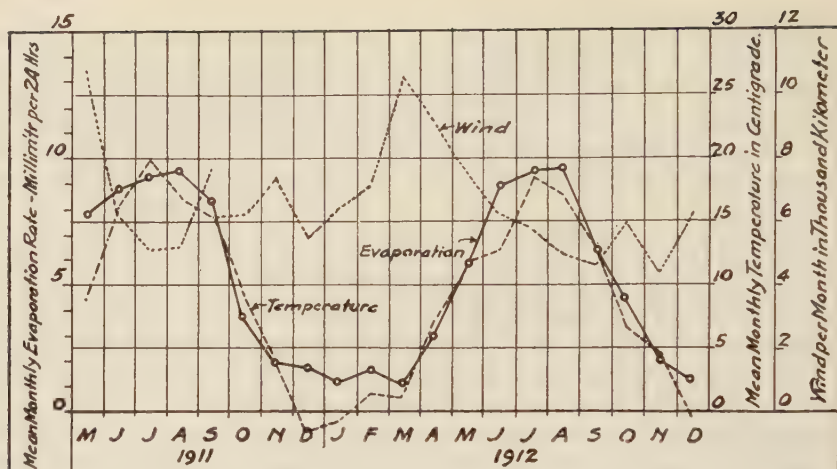


Fig. 4. Evaporation Temperature and Wind at Reno, Nevada.

idity and barometric pressure. In southern California intensive studies (Cummings, 1925), have also been undertaken the practical evaluation of which has not yet been fully established so far as known.

A great number of practical evaporation measurements have been carried out in California and in other western States, by Federal agencies as the Reclamation Service, the Weather Bureau, Department of Agriculture; by California Department of Public Works, Division of Water Resources; University of California, Department of Agriculture, as well as by irrigation districts, power companies, etc.

The losses of water through evaporation are large in Western United States. Losses from reservoirs of the Federal irrigation projects alone cause the loss of approximately 1,235 millions of cubic meters of water each year, a volume large enough to irrigate 100,000 hectares (Houk, 1929). These evaporation losses are unavoidable, there being no way of controlling the evaporation process on lake or reservoir surfaces. The amount of evaporation, however, must be determined with the greatest possible accuracy so that correct allowances can be made in determining the quantities of water available for public water supply, irrigation, water power, or for any purpose.

Evaporation record stations have been fairly well distributed over the various sections of California. Their observations indicate:

- (1) That the mean annual evaporation from reservoirs in California varies from 900 millimeters to more than 1,500 millimeters.
- (2) That reservoirs located near the coast and at the higher elevations in the Great Basin have lower evaporation losses than those in the interior valleys of California.
- (3) That variations in annual evaporation ranging from 30 per cent below to 20 per cent above the mean may be anticipated (Huber, 1935).

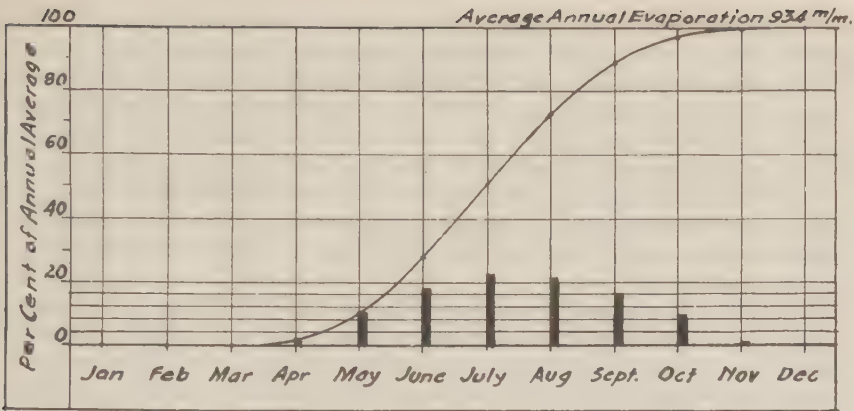


Fig. 5. Evaporation Mass Curve at Crane Valley Lake, California.

As examples of measured evaporation values in California and adjacent western States might be mentioned; Shoshone Reservoir in Wyoming, located at an elevation of approximately 1,650 meters above sea level, has an average annual evaporation of about 750 millimeters; Lake Tahoe, California, at an elevation of 1,900 meters, has an average annual evaporation of about 1,000 millimeters; Elephant Butte Reservoir, located in southern New Mexico, at an elevation of about 1,375 meters, has an average annual evaporation of about 1,680 millimeters. Records at Yuma citrus land pan station, located on a desert mesa near Yuma, Arizona, where the meteorological conditions are unusually favorable for high rates of evaporation, show that a reservoir in that vicinity might have an average annual evaporations as high as 2,100 millimeters.

The evaporation in any one year may be much greater or much less than

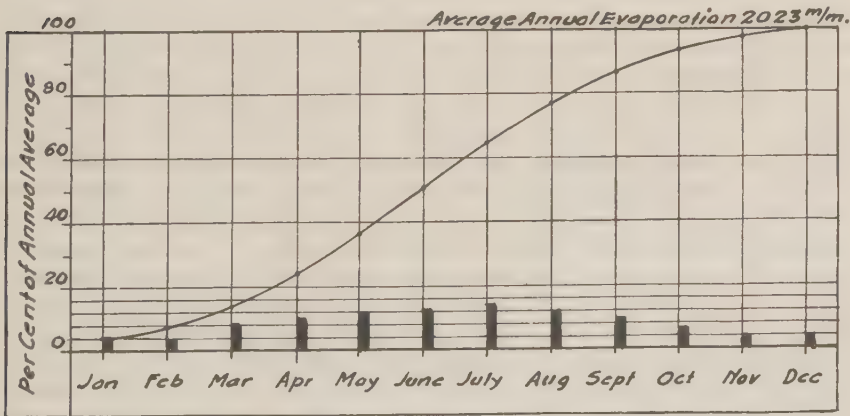


Fig. 6. Mass Curve showing Average of Four Arizona Evaporation Stations.

the average. The actual pan evaporation at Yuma citrus stations has been as much as 3,450 millimeters in a year and as little as 2,900 millimeters, the average for a 3-year period of record being 3,100 millimeters. Depths of water as great as 430 millimeters have evaporated in a month at Elephant Butte Class A, U. S. Weather Bureau station in southern New Mexico. Depths as great as 280 millimeters have evaporated in a month at the East Park floating pan station, on the Orland Federal Irrigation project, in the Sacramento valley, 220 kilometers north of San Francisco. Depths as great as 19 millimeters have evaporated in a day at land pan stations in Arizona.

The Class A station of the United States Weather Bureau is equipped with a circular evaporation pan, 1.22 meters in diameter and 0.254 meter deep, mounted on a timber platform, and provided with auxiliary meteorological equipment consisting of a rain gauge, an anemometer and maximum and minimum thermometers housed in a standard Weather Bureau thermometer shelter. In several instances the United States Department of Agriculture have maintained evaporation stations at the experimental farms on the Federal irrigation projects. As a general rule these stations are equipped with circular pans, 1.83 meters in diameter and 0.61 meter deep, set in the ground to a depth of about 0.535 meter; and are provided with rain gauge, anemometers, maximum and minimum thermometers. Floating pans have also come into use and of various size, the most customary being a pan having 1.22 meters diameter and a depth of 0.254 meter.

VII. River Systems.

As in most arid regions, the drainage of California is simple. For some 320 kilometers on its south-eastern edge it is bounded by the Colorado River, which rises in the Rocky Mountains in Colorado and Wyoming and flows 2,200 kilometers to the Gulf of California. It has no tributaries whatever from California, all eastbound streams from the Sierra Nevada being lost in the desert. On the western coast, though a few rivers reach the sea, such as Klamath, Mad, Eel, Russian, Salinas, etc., they are with a few exceptions relatively unimportant and incidental. The most significant drainage system of California has outlet through Suisun Bay, the Straits of Martinez, San Pablo Bay, San Francisco Bay and the Golden Gate to the Pacific Ocean, by two chief inland rivers which join about 75 kilometers north-east of San Francisco. Both the Sacramento River and the San Joaquin River rise in the Sierra Nevada Mountains, the former having a length of 600 kilometers and coming from the north, the latter having a length of 560 kilometers and coming from the south. Their main courses average along nearly a median line, north and south, through nearly two-third of the 1,055 kilometers north-south length of the State.

The Sacramento River has only a few small tributaries, the Cottonwood, Thompson, Stony, Cache and Putah Creeks, from the great westerly mountain wall, the Coast Range. The San Joaquin River has no tributary

even worthy of the name creek, from the west. The waters of those two streams are being fed almost exclusively from the vast Sierra Nevada Range and the southern end portion of the Cascade Range, as well as by that part of the Great Basin known as the lava-covered Plateau discharging through Pit River and the McCloud River. Their important feeders from the Sierra Nevada are the Feather, Yuba, Bear, American, Consumnes, Calaveras, Mokelumne, Stanislaus, Tuolumne, Merced, Kings, Kaweah Rivers. Farther to the south and discharging into the Tulare Basin at the southern end of the San Joaquin valley are the Tule, White and Kern Rivers. The most important is the Feather River, which has a large drainage area with a high specific as well as total yield. Next in volume of flow come the American, Yuba, Tuolumne, Kings, Mokelumne, etc.

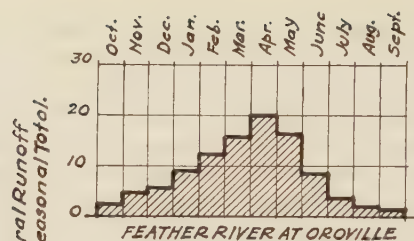
Several streams in southern California, like the Los Angeles, San Gabriel, Santa Ana, San Diego, reach the sea, but all are practically exhausted by irrigation water users, except during winter flood-water. The many streams from the abrupt eastern slopes of the Sierra Nevada all disappear in alkaline "sinks" and playas, like Pyramid Lake, the Mojave River, Mono Lake and Death Valley, and never even in flood reach the ocean by their natural outlet, the Colorado River.

VIII. River Characteristics.

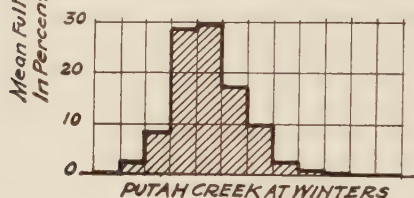
The Sierra Nevada rivers flow through valleys or canyons to 1,200 meters in depth with steep sides, the lateral erosion having scarcely commenced (Russell, 1898). The valleys are narrow, with usually little if any bottom land. The rivers are swift and strong and carry along with ease all of the debris delivered to them by the bordering slopes and tributaries. The rivers are hard at work deepening their channels, and the stage for broadening their valleys has not yet been reached. The Tuolumne, Kings, Truckee and others, are still broken by rapids and cataracts and in many instances are supplied in part by the overflow of lakes. The tireless activity of cutting by these streams is largely due to recent uplifting of the Sierra Nevada mountain block, which has given the steeper slopes and the presence of waterfalls and lakes along their courses is often due to the former existing glaciation in the higher regions.

On leaving the mountains and entering the flat-bottomed valleys these westward flowing streams experience a sudden change and unite to form the Sacramento and the San Joaquin. The Klamath River to the north crosses the complete mountain barrier between the Great Basin and the Pacific Ocean, the Cascade Range as well as the Klamath Mountains and the Coast Ranges. The Pit River likewise sawed itself through from the Great Basin to the central valley of California.

All streams vary in flow with the seasons but in California the variations are seemingly more marked than elsewhere. Many streams have a low water flow of only 2 to 5 per cent of the maximum. Again the range in discharge from year to year varies. Some northern rivers range from one-half to twice the mean and southern rivers exceed this variation.

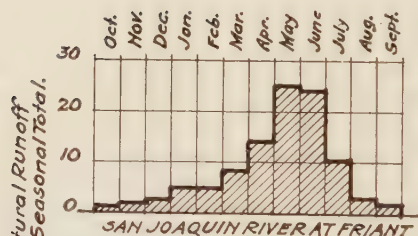


TYPICAL HIGHELEVATION
WATERSHED
SNOW-FED STREAM.

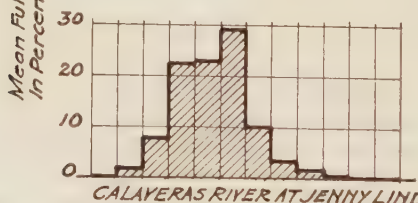


TYPICAL LOW ELEVATION
WATERSHED
RAIN-FED STREAM

SACRAMENTO BASIN.



TYPICAL HIGH ELEVATION
WATERSHED
SNOW-FED STREAM



TYPICAL LOW ELEVATION
WATERSHED
RAIN-FED STREAM.

SAN JOAQUIN BASIN

AVERAGE MONTHLY RUNOFF
IN PERCENT OF SEASONAL TOTAL

Fig. 7.

The usual California river coming from the high mountain regions has generally two types of floods. A winter flood may be caused by excessive rains in the foothill region—up to 1,000 meters in elevation. Spring floods usually come from melting snow above elevation 1,000 meters. As a rule, the spring floods upon which irrigation depends, come from melting snow. These floods are not all at the same time. Due to greater elevation of the mountains, the rivers of the southern Sierra Nevada, the San Joaquin, Kings, Kaweah and Kern, have floods a month or so later than the rivers of northern portion of the mountain range, the Sacramento, Feather, Yuba, American, etc. For irrigation the southern rivers are best, but in all of them the natural flow falls away just as the greatest demand comes on, —June, July and August. Hence the great need for storage reservoirs for conserving the early portion of the runoff, as well as the late fall and winter runoff.

In the hydraulic study of any river for a reasonably complete development it at once becomes apparent that all the water that flows cannot be used. Reservoir sites do not exist nor would the expense be justified to construct reservoirs to fully regulate the stream at all times. There are few exceptions to this. Probably the best site for fully regulating a part of the stream is at Lake Almanor on the North Fork of Feather River, where a reservoir site has been developed of 1,613 million cubic meters capacity, that will fully conserve all water coming from about 1,300 square kilometers of watershed. The general statement is true, however.

It follows that in a hydraulic study of any river there must be taken into account many factors such as minimum and maximum stream discharge, area of land available for irrigation, size, location and cost of storage sites and several requirements of irrigation. No stream would be developed merely for the extreme minimum discharge nor for the maximum. Probably the mean discharge is a fair statement of the amount that might be used. The power study would follow similar lines but the presence or absence of good storage sites is a large element in determining the maximum development and similar considerations govern in a major development for public water supply.

IX. Surface Water.

The moisture-laden winds blowing in over California from the Pacific Ocean precipitate great amounts of water annually upon its surface. Most of this falls as rain or snow upon the elevated slopes and mountain areas. In higher elevations with lower temperatures the mountains are more effective in reducing the moisture-holding capacity of the oncoming winds than are the low flat lands, so that these winds in drifting toward the low pressure areas, cause the atmosphere to discharge a greater water volume to these areas than to the lower level regions. This precipitation, as rain, immediately sets out on its journey to the ocean, being retarded more or less by topographic and relief conditions and upon the porosity of the rocks

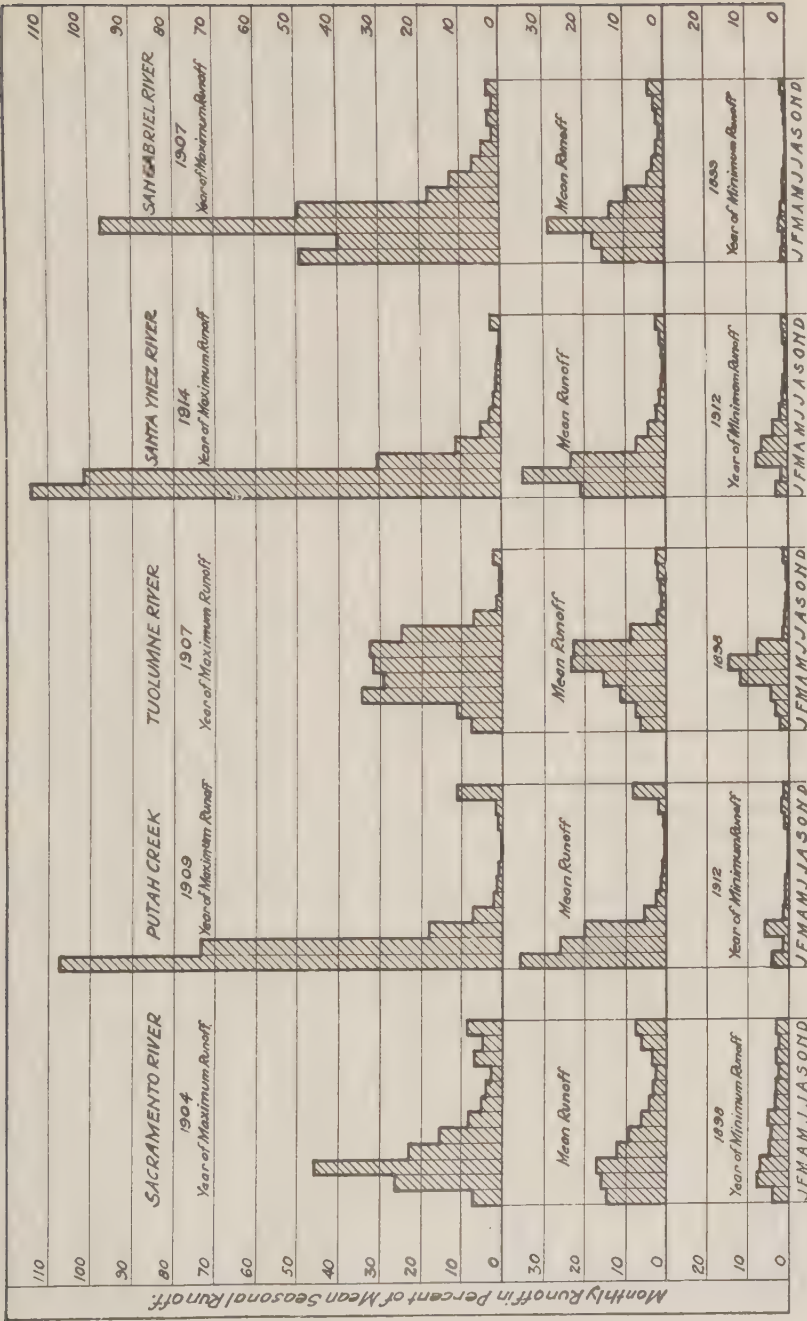
and soil, of the watershed. As snow, it remains in the higher portions of the mountains until the warmer season approaches then to melt and flow down the rivers to the sea.

The water producing areas of California are the mountains. Influenced by the topography, elevation and exposure of the divers localities, varying amounts of precipitation fall on the collecting areas and the runoff derived from it also varies in a similar manner. The runoff is least from the desert regions in the south-east and greatest in the northern areas of the Coast Ranges contiguous to the Oregon boundary. It ranges from 25 millimeters in depth over the land annually from the least rain-producing regions of the south to over 2,500 millimeters in depth from the greatest rain-producing areas of the north. Between these two extreme regions separated more than 1,000 kilometers, is the water-yielding area, 60 per cent the area of California.

In each area only a portion of the water cast from the clouds ever reach the stream channels, the rest is dissipated through evaporation. The fraction of the precipitated water finally appearing as streamflow in each season may be less than 25 per cent and more than 75 per cent of the total, according to the amounts falling, the contingencies of the season's weather, and the circumstances of topography and geology of the watersheds.

A small portion of the water percolates into the ground, forming an important tardy supply, as spring flow or low water flow, in streams, in general, dry season flow, and are the principal waters available when the great volume runoff has subsided. Their total amount, however, is small for 75 per cent of the runoff from California's mountains concentrates in the stream channels, flows rapidly down the water courses and passes by the low-lying agricultural lands within forty-five days after its precipitation (Bull, 4). It follows that these volumes of water have been of slight use to the lands compared to when stored in the mountains and released in times of need. Following precipitation so closely, the waters appear in the stream channels in fluctuating flows having a striking similarity to the periodic occurrence of precipitation. Fig. 8 represents the hydrographs of five streams each typical of a separate section of California. They show the runoff month by month, for the greatest year and for the least, as well as the mean monthly flow of all the years of record. It is seen how the bulk of the waters runoff their mountain catchment areas during the winter months and how only meager quantities flow in the streams during the middle and late summer. The great variation between the runoff of the maximum and minimum years shows the wide limits between the seasonal runoff fluctuations, and how, in the smallest season, the usual scanty summer flow is much reduced and this much earlier in the season than in other years.

California presents three distinct regions characterized by the stream systems which drain them and in the stream channels of its surface water. (1) The 55 streams draining the coastal sections discharge their waters directly into the Pacific Ocean. (2) The Sacramento Basin and the San Joaquin Basin are each drained by a single, very extensive river system,



CHARACTERISTICS OF RUNOFF FROM CALIFORNIA STREAMS

Fig. 8.

the waters from which merge in the delta region and are finally discharged into the Pacific Ocean through Carquinez Strait and the Golden Gate. (3) The Great Basin streams have no outlet into the ocean with the exception of the Pit River, as before noted. Each one of the streams empties into a "sink" or playa lake at the lowest part in the closed basins of which the Great Basin is made up.

The streams of the Sacramento and San Joaquin Basins may be divided into two classes as regards their runoff characteristics. To the first class count those from the foothills the runoff of which originates almost entirely from precipitation falling as rain; while in the second class will be found those from the higher mountain areas, the runoff of which originates in large measure in precipitation falling in the form of snow. The chief difference has to do with the period that elapses between the time of precipitation and the occurrence of maximum rate of runoff resulting therefrom.

As stated, precipitation falling as rain appears as runoff in the stream within a very short time, while that which falls as snow, especially in the higher mountain regions usually forms a heavy snow blanket which does not melt until May or June, then causing peak flow in the streams traversing the valley floor area at a time long after the normal precipitation in the valley has passed.

Because of the existence of long and continuous records of stream measurements in California from a large number of streams distributed over the State it has been possible to make reasonably accurate estimates of the annual volume of water appearing as runoff in the various sections. Such estimates have been worked up by the California Department of Public Works, Division of Water Resources, and by the Water Resources Committee of the National Resources Board, based upon the stream measurements continuously made by the United States Geological Survey, Water Resources Branch.

The area of drainage in each section lying above the main body of agricultural lands, seasonal runoff from these areas as regards mean, maximum and minimum years, as well as their percentages of total runoff contributed from each section is as follows:

Table 5.

Section	Area above Agric. lands Square Kilometers	Mean Runoff		Maximum Runoff		Minimum Runoff	
		Million Cubic Meters	Per Cent	Million Cubic Meters	Per Cent	Million Cubic Meters	Per Cent
North Pacific . .	42,846	33,101.63	37.00	62,275.41	25.82	12,814.42	37.40
San Francisco Bay	5,747	1,018.02	1.12	3,841.42	1.58	52.91	0.15
Central Pacific .	24,574	1,265.47	1.41	4,976.39	2.06	114.84	0.32
South Pacific . .	10,622	2,980.06	3.32	11,829.21	4.90	67.10	0.18
Sacramento Basin	55,478	31,084.09	34.80	101,397.19	42.02	16,864.68	49.23
San Joaquin Basin	47,081	15,210.90	17.00	42,005.55	12.40	2,888.41	8.40
Great Basin . . .	22,989	4,808.70	5.35	14,982.58	6.22	1,509.08	4.40
	209,337	89,468.87		241,307.76		34,311.47	

The seven topographic sections of California have each one predominating characteristics. Of these the Sacramento River Basin is the largest in yield. It comprises not only all the area lying between the Coast Ranges and the Sierra Nevada Mountains as far south as the Consumnes River, but also the drainage area of the Pit River, to the east of the mountains and in the north-eastern corner of California. This large basin contains one-fourth of the water-producing area and with the exception of the North Pacific section, it produces more than any other of the sections and one-third of the waters of California. The mean runoff is 575,000 cubic meters per square kilometer or 575 millimeters in depth.

The San Joaquin River Basin is the largest in area of the sections but produces only one-sixth of the waters. This basin comprises the entire area between the Coast Ranges and the Sierra Nevada Mountains, south from Suisun Bay and Consumnes River, down to Tehachapi Pass. The mean runoff is 323,000 cubic meters per square kilometer or 323 millimeters in depth.

The third largest is the North Pacific section, which includes all the streams draining into the Pacific Ocean northward from San Francisco Bay. It contains one-fifth of the water-producing area, but its streams contain over one-third of all the waters of California. This is a greater yield than in any other of the sections. For equal area it produces one-third more water than the Sacramento Basin and over twice that of the San Joaquin. The mean runoff is 772,000 cubic meters per square kilometer or 772 millimeters in depth. This section contains the most productive drainage basin in California, the Smith River. Although its watershed is only 1,624 square kilometers the mean annual runoff is 4,201.615 million cubic meters or 2,588 millimeters in depth.

The Central Pacific section drains into the Pacific Ocean southward from San Francisco to Ventura, for its size is the region of smallest water yield. From its 8.5 per cent water-producing area the yield is only 1.4 per cent of the total mean for the State. The mean runoff is 51,500 cubic meters per square kilometers or 51.5 millimeters in depth.

The South Pacific section drains into the Pacific Ocean from Ventura south to the Mexican border. From its 5.1 per cent water-producing area the yield is only 3.3 per cent of the total mean for the State. The mean runoff is 280,000 cubic meters per square kilometer or 280 millimeters in depth.

The San Francisco Bay section is the smallest of the topographic units, and includes the area adjacent to San Francisco Bay, exclusive of the Sacramento and San Joaquin Rivers. The area is 2.75 per cent of the water-producing area and its mean yield is 1.15 per cent. The mean runoff is 177,150 cubic meters per square kilometer or 177 millimeters in depth.

The Great Basin, comprises the area easterly from the Sierra Nevada mountain system, and whose waters do not reach the ocean. One-tenth of the water-producing area lies in this region but it yields only one-twentieth of the waters. The mean runoff is 209,000 cubic meters per square kilometers or 209 millimeters in depth.

There is a great difference between the sections enumerated in which their waters run off from the collecting areas. Generally the regions of least productivity have the greatest variability in runoff and demand the largest capacities in storage works to equalize their variable stream flow.

The storms that drench the uplands and mountain regions or mantle them with snow, precipitate lesser amounts of water on the lower flat lands, and this almost entirely as rain. Lacking the necessary surface slope to run off, these rains falling on the lower lands are largely absorbed in the ground or detained in pools and depressions or saturating the soil cover and are later evaporated. Only during extremely heavy rains of infrequent occurrence do the flatlands contribute runoff to the stream channels.

X. Groundwater.

In various regions of California groundwater is of considerable importance for increasing the water supply when the surface runoff of the streams becomes low or disappears. In some regions the groundwater conditions have been studied for long periods, in other regions they have received scant attention, except from the population of these regions who are often dependant upon these sources of water for supplying their homes and their stock with water.

In the North Pacific section it is believed (Huber, 1935), although no data concerning it is available, that the topographic and geologic character of the region is such as to preclude the possibility of the occurrence of underground water to any material extent or in any substantial volume.

In the San Francisco Bay section it is believed underground water of material volume might be found in two areas. One of these areas, in the Santa Clara Valley has been dependent upon pumping from wells for its water for irrigation. However, the draft upon this underground water has exceeded the replenishment, and the elevation of the water surface has been steadily sinking. Flowing wells were brought in thirty years ago in the area at the mouth of Alameda Creek, known as the Niles cone. The city of Oakland, for many years secured a portion of its domestic supply from this source. The wells finally ceased to flow and the water level receded continuously and the field finally abandoned as a source of domestic supply.

Central Pacific:—There are several areas, of small extent, in this section from which water is secured by pumping from wells. Data as to their annual production are not available but is believed to be very small.

South Pacific:—On account of the variable character of the surface runoff of the South Pacific section, were it not for the extensive alluvial deposits that underlie a large part of the agricultural and habitable lands much of the total water yield would flow into the Pacific Ocean unused.

In the northerly section of the South Pacific section, the generally narrow and steep slopes of the stream beds are, as a rule, unfavorable for the construction of surface reservoirs of sufficiently large capacity to equalize the variable runoff. The greatest storage and regulation of water takes



Bullards Bar Dam and Reservoir, Yuba River, northern Sierra Nevada. Height above stream-bed 58.25 m. Highest Overflow dam in California. Storage Capacity 38.85 million cubic meters also serving as debris storage for hydraulic mining. Power Plant; Head 50.6 m. Installation 6,900 Kw. Completed 1924.

Courtesy Pacific Gas and Electric Company, San Francisco, California

place in the alluvial fans and cones of relatively coarse material that underlie the areas in the lower reaches of many of the streams of this section. The capacity and extent of utilization of underground reservoirs in the South Pacific section can best be realized by a comparison of estimates of natural surface runoff, total quantity of water utilized and amount of utilized water regulated and pumped from underground reservoirs:

Mean average seasonal runoff	1,357	million	cubic	meters
Total seasonal yield utilized	987	»	»	»
Seasonal yield made utilizable by groundwater storage and pumping	803	»	»	»

In addition to these supplies a seasonal amount of 357.7 million cubic meters is imported from the Owens River. Some of the imported water also is used by underground storage and pumping. Further supplies to a maximum of 45.3 cubic meters per second is to be imported from the Colorado River.

Sacramento and San Joaquin Basins:—Large groundwater reservoirs are utilized in the San Joaquin and to a lesser extent in the Sacramento Basin. Pumping from wells with electrically driven equipment and modern construction combustion engines have been developed to a very great extent in these basins. A large part of the surface runoff from the surrounding or adjacent mountain areas and surface irrigation applications in excess of net use requirements find its way into the underground reservoirs, part of which constitutes a re-use of percolation losses from surface irrigation, makes for a high degree of utilization of the total available supply with a very small amount of surface storage regulation, to equate seasonal runoff, the limit of which is reached only when the net use of water approaches the consumptive use. The use of underground reservoirs in these areas affords the only means of providing the large amount of cyclic storage required to equate the extremely variable runoff and bring the available supply in consonance with the demand. Operated in conjunction with a limited amount of surface regulation, the utilization of underground reservoirs in the upper San Joaquin area results in the most economical, flexible and complete water supply utilization possible of accomplishment.

Wells and pumping plants with an aggregate capacity of 583 cubic meters per second, or 1,529.56 million cubic meters per month, if operated continuously, are in operation in the upper San Joaquin valley. This monthly capacity is about equal to the average total combined stream flow in June, the month of maximum runoff for San Joaquin, Kings, and Kern Rivers. The usable underground free water storage capacity in the area aggregates over 24,660 million cubic meters.

Great Basin:—The extent of groundwater reservoirs and their utilization is limited. There are many relatively small valley fills where contributions to groundwater are made by surface runoff from adjacent mountain areas, by rain falling directly on the valley areas and by underflow from certain canyons.

PART THREE

The Principal Uses of Water.—Flood Control.—Conservation of Water.

I. General.

The value of good water is more generally recognized in the arid regions of the earth than elsewhere. In such regions, water is usually evident in the form of torrential floods, which rush from the hills and mountains to waste themselves upon the plains below, or are lost in the sea. What little water remains is found running in tricklets down comparatively dry washes or stream channels of Wadi-type, or in springs, or potholes. During the long dry months of the summer, these water holes and springs were in the early days the only source of supply to slake the thirst of man and his wandering herds.

Abundance of water of good quality is one of the three great prime necessities of human life (air, water and food). Of these the most necessary is air, the second is water and the third is food. Humans can live only a few minutes without air, a few hours without water, and a few days without food. Since air is freely acquired without human effort, the prime necessity to be provided is, therefore, water, and in such abundance and quality as to meet mans needs. Good water for domestic use must be free from objectionable minerals, suspended matter, color, foreign tastes, odors, and disease-bearing germs. Any water meeting the domestic requirements is eminently suitable also for stock, for irrigation and for industrial purposes.

In California and the south-western regions of the United States water was always the greatest of all problems. In New Mexico and Arizona irrigation was in extensive use before the Spaniards arrived and although there are no records of such early use in California, the location of the missions was entirely dependent upon sites having an abundance of good water for the people living in them and for the great numbers of cattle on their lands. With the discovery of gold water became a prime requisite of that industry, when water was on hand mining prospered, when the dry summer came men were often lying idle—plenty of water meant plenty of gold. Water was very valuable, many fights and killings “up the creek” took place over the rights to water and about its use and misuse.

With the coming of modern irrigation about 1885, water became still more important for the raising of crops, products that always were in demand and at rising prices. As the country developed, large cities sprang

up industries started, with demand for light and power, hydroelectric development started on a large scale basis and the modern era had arrived with strife about the rights of water, on a grander scale. So it was in California's early days, and so is today the possessor of a good well or water right a subject of envy to his neighbors. In the Holy Land, Abraham and his sons fought valiantly to obtain possession of the springs that made their abundant flocks and attendant wealth possible. After one of the great famines in the land of Abraham, Isaac in search of water and pasture went to Gerar. There he waxed great and grew fat and the Philistines envied him, "for all his wells which his father's servants had digged in the days of Abraham, his father, the Philistines had stopped them and filled them with earth." Isaac departed therefrom.

"And Isaac digged again the wells of water, which they had digged in the days of Abraham, his father; for the Philistines had stopped them after the death of Abraham; and he called their names after the names by which his father had called them."

And Isaac's servants digged in the valley, and found there a well of springing water. And the herds-men of Gerar did strive with Isaac's herds-men, saying, The water is ours; and he called the name of the well Esek; because they strove with him. And they digged another well, and strove for that also; and he called the name of it Sitnah. And he removed from thence, and digged another well; and for that they strove not; and he called the name of it Rehoboth; and he said, For now the Lord hath made room for us and we shall be fruitful in the land." (Irving, 1929.)

The strife for water, which is so well illustrated by the above quotation from Genesis has been going on from that day to this, in regions where the climatic conditions are similar to those which existed two thousand years ago in the lands occupied by the tribes of Israel. Up to this day the strife about water goes on only tactics have changed. In the fights between the City of Los Angeles and the farmers in Owens Valley in recent years, dynamite and shotguns have been found useful when the strife was at its hottest. Dams, gates, conduits were wrecked in the fight by one side and highpressure thumbscrew methods of abuse were used on the other side.

Indicative of the importance of water problems in California is the establishing of a Division of Water Resources under the Department of Public Works, fifteen years ago. This authority is charged with the study of the water resources of the State and with all problems pertaining to water in regard to: irrigation, power, flood control, municipal water systems, hydraulic mining, navigation, groundwater problems and salinity control. A very great amount of work regarding the water resources has been accomplished and comprehensive plans have been worked up for their conservation. The first units of this Central Valley Plan are now in their first stages of construction.

As discussed in Part II, only one-half of the wide expanse of California contributes much to the waters of its streams. The other half, lower in altitude and more level of surface, is favorably disposed for occupancy

by man, and its populated sections need water in order that their industrial expansion may continue and their communal growth progress steadily onward. The production of food, the generation of power, and the supply of water for domestic use, in the drier half of California, are largely dependant upon the waters of the streams which have their source in the more elevated regions. The farmer and orchardist relies upon the streams during the warm, dry summers for supplementary moisture to mature his crops and upon their hydroelectric energy to pump his irrigation waters. The electric energy generated by the falling waters of the streams as they descend the mountain's slopes, furnishes power and illumination to the cities and industrial centers, heat and light and means of operating many conveniences to the entire social state. But most of all, the cities, towns and villages, the pleasures and comforts of their congregated peoples, require these waters in abundance for drinking and household purposes. The expansion of all these benefits to include larger populations, demands increased supplies of water for the future with uninterrupted service in purity and in sufficient volume, at all times of the year and in all successive years alike.

The vital importance of water in the economic development of California is succinctly shown in the history of the State's production statistics. The advance to a very favorable place in comparison with the other States of the Union was made without any increase in the total area in improved farms. In fact, fifty years have elapsed since the aggregate area in improved farms in California has increased. Although there are 9,315,000 hektares of land susceptible of agriculture within California, the enlargement of the area tilled ceased when but half of the total land had been brought under cultivation. As a result of the unprofitable farming conditions obtaining on the remaining millions of hektares the area under cultivation did not further enlarge; the experience of the practical farmer limited the total area cultivated to but half of the agricultural lands (Haley, 1928). Some additional areas having inadequate natural moisture have since been added to the total area of improved farms by developing accessory water supplies, but the abandonment of other areas previously farmed has compensated in their summation and so the total acreage in improved farms has remained practically unchanged for fifty years.

The following list shows the farm land situation as of the last federal agricultural census of January 1, 1935, compared with the census of 1925;

Table 6.

Farm land according to use	Hektares	
	1934	1924
Crop land harvested	2,604,383	2,317,734
Crop failure	186,100	398,884
Crop land, idle or fallow	658,165	685,925
Plowable pasture	1,201,848	1,228,533
Woodland pasture	2,031,523	1,712,313
Other pasture	4,664,034	3,892,166
Woodland not pastured	279,615	177,183
All other land in farms	641,720	731,628
All land in farms, 1934 and 1924 resp. . . .	12,327,388	11,144,366

It is seen that the area of all land in farms increased 15 per cent and the crop land area harvested increased 10.6 per cent in 10 years or 1.5 and 1.0 per cent per year respectively. This increase during the last decade is largely due to the completion of a number of water conservation projects for irrigation such as the Don Pedro Dam completed in 1923, the Exchequer Dam completed in 1926 and the Melones Dam completed in 1927. In addition to these dams a number of smaller irrigation water conservation projects were carried out like the Dwinell Dam of the Montague Irrigation District in northern California, the Webber Creek Dam in Eldorado County, near Placerville and others.

II. Public Water Supply.

The problem of distribution of water to urban communities in California varies with the conditions and may be considered under categories of quantity and quality. Quantity, is a problem in arid and semi-arid communities of growing population. Quality, the desideratum being a water that is clear, tasteless, free from pollution and soft, does not lend itself so easily to regional distribution, turbidity occurs where the source is a river and is slight in impounded waters; taste is a seasonal and at times a local phenomenon; pollution arises from the character and density of populations; and hardness from the soluble character of soil and rocks.

The larger problems of water supply in arid and semi-arid lands are in general known. In humid areas where many people reside the problem of water supply becomes acute in those regions where the source of supply is drawn from secondary streams. A city tapping a large river or its tributaries are generally immune from shortage even during excessive droughts, as for instance in 1930 when during the severe droughts, none of the large cities on the Mississippi River suffered shortage. In eastern cities the drought conditions caused water supply boards to prohibit, in instances, the use of water for lawns and the washing of automobiles. Schools were closed, Monday wash day banned, tub baths limited to one a week and even water shortage threatened (Brown, 1931).

In California, as generally throughout the West the importance of water, as already pointed out, is earlier recognized and measures taken to insure an adequate supply. San Francisco early had in its Spring Valley system an adequate supply and with the now completed Hetch Hetchy system, the city will have 25,110 hectares in watershed with a capacity of 444.07 million cubic meters and this will yield, even during a succession of seven or eight seasons of scanty rainfall, a daily quantity in excess of her needs. The East Bay cities on the San Francisco Bay will, since the Pardee Reservoir with a watershed of 5,184 hectares was completed in 1928, having a capacity of 273.84 million cubic meters, be in a position to meet the demands of these rapidly growing cities for many years to come. An eighteen months supply is generally held and such reserve provides safety against water shortage in the District in case of unforeseen accident to the 166

kilometers long aqueduct line from the Pardee Reservoir at Lancha Plana on the Mokelumne River to the various distribution reservoirs in the East Bay cities.

Los Angeles, settled in 1781 on the Los Angeles River, obtained from King Charles III of Spain by royal decree the ownership of all the waters of the river in perpetuity. Until 1914 this was practically its only source of water, and it was considered sufficient to supply a population of 250,000.

When Los Angeles passed the quarter century mark and the Los Angeles River, described as a stream whose bed must be sprinkled to keep down the dust, became inadequate, the city tapped the Owens River, 400 kilometers away. Owens Valley is about 440 kilometers long, lying between the Sierra Nevada Mountains on the west and the White Mountains on the east. Practically all the drainage is from the Sierra Nevada between Mount Lyell and Mount Whitney. The river empties into Owens Lake, and the latter has no outlet. Previous to 1905 the valley had a population of about 3,500 (Brown, 1931), who gained a livelihood by farming on lands irrigated by the river, since the rainfall of the valley is light—probably not over 125 millimeters per year.

Since the founding of Los Angeles, water in Southern California has become increasingly valuable. Simple diversions from surface streams soon were superseded by wells drawing on ground water in the artesian belts. When these wells ceased to flow, pumping from deep wells was resorted to, even for the irrigation of alfalfa and citrus crops. The rapidly growing valley in which Los Angeles is the largest city soon found it necessary to seek outside sources to supply the increasing demand for water. This led to the construction of the Owens River Aqueduct which was completed in 1913. Now, by the joint efforts of 13 cities in the metropolitan district, construction is nearing completion on the 420 kilometer aqueduct to convey water from the Colorado River.

The early californians faced economic disasters while dependent on the surface runoff for their water supply. In the two-year drought that began in the fall of 1862 and lasted until the fall of 1864, when it was reported that "not more than a trace of rain" fell during the whole preceding season, the dry feed on the ranges was soon exhausted and the excessively large herds of cattle died by the thousands. One cattle baron, Abel Stearns presiding over a domain of 61,000 hectares, including the original Spanish grant ranchos of Los Coyotes, La Habra, San Juan Canjon de Santa Ana, Las Bolsas y Paredes, La Bolsa Chica, and part of the Alamitos in southern California, lost 50,000 head of cattle and was reduced to the verge of bankruptcy. His vast landed possessions were advertised for sale in 1863 on account of delinquent taxes, which totaled only a little over 2,000 dollars. This drought during the sixties practically put an end to the cattle industry in the region and sheep took the place of cattle during the following decade. Then came another long drought, from 1874 to 1877, which resulted in enormous losses to the sheep raisers, 22,000 head died from lack of feed on the Rancho Sentinel alone, a part of which is the present town of Inglewood, southwest of Los Angeles. The next

drought, from 1893 to 1904, placed severe test on the municipal means of developing ground water, which had come into general use.

Among the early ambitious efforts for the development and distribution of water supply in the valleys and on the coastal plain adjacent to Los Angeles, was a ditch built under the direction of the mission fathers from the west side of the San Gabriel River, where it leaves the mountains, to divert water for irrigation around the Mission San Gabriel, nearly 25 kilometers away. Another outstanding undertaking was the construction, soon after the founding of Los Angeles in 1781, of the Zanja Madre, or the "Mother Ditch", extending two miles from the Los Angeles River to a point a short distance north-west of the Plaza. The Zanja Madre transported the waters of the Los Angeles River within easy access of the old village, whence water jars could be filled or distribution to the irrigated lands could be effected by means of small ditches. Early in the nineteenth century its course was extended through what is now Pershing Square.

A number of Cienegas, or large springs, were also in early days to be found along the bottom lands of the Los Angeles River (Schuyler, 1879); those west of Los Angeles River from which issued Ballona Creek; of a large one near Pomona, and of two outstanding ones of over 120 hektares area each, near San Bernardino. Not less than 18 cienegas were counted in a distance of 8 miles along the rim of the plateau of the southerly edge of the present city of Pasadena. Three of these springs furnished water for irrigation of an area of 560 hektares. Artesian wells were very numerous but today they as well as the springs have long since disappeared or ceased to flow as the groundwater table lowered with the increased draft.

In recent years California has suffered severe droughts, as for instance in 1919 and still more severe in 1923-24. As the hydroelectric power producers do not carry storage over from one year to another these years were most detrimental to power production. Many of the storages had in the middle of the summer of 1924 very little water. One system in northern California was 53 per cent short of water as compared with normal, another was 60 per cent short. The San Joaquin valley suffered probably more than any other portion of the State. On the Kern and Kaweah Rivers only 3 or 4 out of some 35 irrigation canals were carrying water, whereas in the previous year the Kaweah had carried a flow of 16.50 cubic meters per second at the end of July. The Kern on that same date carried only 3.40 cubic meters instead of its normal for that date of 38.30 cubic meters per second. Huntington Lake, typical of the basins from which a large part of the southern California's hydroelectric power is derived, collected 65.4 million cubic meters in the up to that time driest year in 1919, and only 21.4 million cubic meters in 1924.

In areas of limited precipitation, conflicts frequently arise, as we have seen, over rights, and it is not strange that, when Los Angeles went beyond her borders for water, trouble followed. The intake of the Los Angeles system on the Owens River was below the headgates of the lowest irrigation ditch (Outlook, 1927), and consequently the city could not deprive the farmers of water, but on the contrary it took at the beginning only such

water as would have gone into Owens Lake and eventually evaporated. In reality Los Angeles benefited the Owens Valley farmers by connecting them by rail with the outside market. This boom acted as a boomerang since it afforded inducements to settlers, and the population by 1920 had doubled and the tourist trade had become inaugurated. With the increase in population and a corresponding withdrawal of more water from Owens River by the settlers, Los Angeles found in 1923 that the leavings were not sufficient for the city's needs and began to buy land from the farmers to lessen the irrigation drain. Altogether 80 per cent of the irrigation lands of the valley were purchased. In 1924 there was an outbreak by the farmers, aqueduct waste gates were opened or dynamited and about 757 million cubic meters of water were turned into the desert.

Today Los Angeles is moving toward the one and one-half million mark in population, is looking forward to a city of 2,000,000 people and must have more water than can be gained from the Los Angeles and Owens Rivers. Work is in progress of utilizing the Mono Lake Basin farther to the north to tide her over until around 1940, the aqueduct from the Colorado River, at Parker, 420 kilometers away will be brought in—to carry 1,340 million cubic meters annually if the allotted 42.50 cubic meters per second (1500 cubic feet per second), flows continually. The Colorado River has not an adequate amount of water for all the requirements of this region. The United States Geological Survey estimates that at Parker, when the water is first turned from the river for use, the annual supply will be about 11,833 millions of cubic meters. Irrigable lands below Parker will demand 12,223 million cubic meters, in Mexico 4,141 million cubic meters is probably ultimate need for irrigation and Los Angeles and other southern California cities are calling for 56.7 cubic meters per second, equivalent to 1,786 millions of cubic meters for domestic purposes, a total of 18,150 million cubic meters; and if the estimates are correct, there will be an annual shortage of 5,927 million cubic meters of water in the lower Basin (Brown, 1927).

On September 28, 1542, Juan Rodriguez Cabrillo first sighted Point Loma, which lies within the military reserve of Fort Rosecrans at the present city of San Diego. Ever since that time white men sailed into the harbor of San Diego to take on fresh water, and since that time water has been a major problem for the inhabitants of this promising locality. In fact the first irrigation development in what is now the United States was built about 1800 by the Franciscan missionary fathers, of which Junipero Serra was the leader. This development consisted of a small diversion dam on San Diego River, 23 kilometers from its mouth and a ditch for irrigating the mission lands. Today the City of San Diego, whose 150,000 people have a great water supply system, have built a number of storage works, the last one completed being El Capitan Dam, an hydraulic-fill-rock embankment structure.

When the Pueblo of San Diego and Mission San Diego de Alcalá were established under Spanish grant as the first settlement of Alta California in 1769, all the water in San Diego River was made the property of the

pueblo. For many years this fact was forgotten, but when recalled it led to serious legal complications in water rights. After extended court action the city was decreed to possess in fee simple the prior and permanent rights to use all the surface and underground waters of San Diego river from its source to its mouth.

Since establishment of the pueblo, average population growth has been 1,000 per year, but more than one-half of the present population came in the last fifteen years. This redoubled population has required great increase in water facilities and the development completed with El Capitan is but the first of three reservoirs in San Diego river drainage basin which will supplement existing sources of supply. In 1929 the city had a developed supply of about 57.8 million liters daily, from three sources, against 217 million liters daily total probably available from seven sources ultimately, enough for 750,000 people, by local developments. Allocation of 4.40 cubic meters per second of domestic water supply from the Colorado River has been secured. This supply would serve an additional 1,000,000 population. While in 1902 water consumption averaged 279 liters per capita per day in San Diego, it has increased to 440 liters by 1930. For 1931 the total daily use averaged 65.5 million liters with a maximum of 107.3 million liters on July 14. (Savage, 1929).

The city of San Diego, situated in a semi-arid territory of infrequent rainfall, and with a population of 150,000 and a rate of growth of 50 per cent between 1920 and 1930, must of necessity use greater foresight in securing an adequate supply of water, and provide greater storage capacity than most other large cities on the west coast. There is no one source of supply big enough in San Diego County to meet the requirements of the city of San Diego, and dams have to be built in various watersheds to catch and store the flood waters during the years of sufficient rainfall to tide over the years of drought. Conditions in San Diego County that effect the storage of water supplies, and the precautionary measures taken to safeguard the purity of water, especially in view of the fact that all of the artificially created lakes and reservoirs have always been used for recreational purposes, are rather unusual (Wueste, 1926).

Very generally speaking, as one travels east from the Pacific Ocean in San Diego County a belt of elevated coastal bench about 15 kilometers wide is first crossed. This ends abruptly against a porphyry dike cut by defiles where the major drainage channels break through to the coast. Then comes the true runoff-producing area of the county, a 50 to 65 kilometer wide belt of broken and mountainous territory bounded on its eastern margin by a divide, 1,200 to 1,800 meters in elevation, which overlooks the Imperial Valley. The highly irregular topography of this mountainous area makes it remarkably rich in dam and reservoir sites but is devoid of natural lakes.

The rainy season begins in December and during the three or four following months the dry water courses are periodically converted into torrential streams flowing swiftly from steep watershed slopes and cascading down boulder-choked gorges to the sea. Thus there are no perennial streams

and the few natural lakes filled during the rainy season are evaporated to dryness during the summer months. Under these conditions when artificial lakes are formed by the construction of dams the attraction of a lake playground immediately creates a demand for recreational use.

Groundwater supplies in this region are very limited and are regarded as emergency sources only. The only means to an adequate water supply is the construction of reservoirs which will impound and retain from season to season the erratic winter flood flows, thus securing a regulated gravity supply.

The runoff-producing area in San Diego County consists of about 5,200 square kilometers, of which about one-third is in the Cleveland National Forest. Altogether about two-thirds of the runoff-producing area is still public domain. The watershed areas are predominantly granitic in character, incompletely overlain with soil suitable for agriculture, sparsely wooded and sparsely populated.

The Cottonwood-Otay system furnishes about 75 per cent of the city's water which must finally pass the lower Otay reservoir. This reservoir is also used for public recreational use and here certain provisions and regulations have been put into effect to prevent the waters from becoming contaminated or unsafe.

The San Diego reservoir system includes 5 of the 9 major impounding reservoir developments within the county. The city controls 50 per cent of the county's available drainage collection area. Further developments will doubtless be made by the city by reason of the need for more water.

Sacramento, the Capitol city of California derives its domestic water supply direct by diversion from Sacramento River. For a number of years the city has been contemplating a new supply from Silver Creek a tributary to the South Fork of the American River above Placerville about 100 kilometers north-east of the city. This will insure to the city a first class water system in connection with the development of hydroelectric power for this city whose present water supply system suffers from turbidity of the river and has to be treated by filtering and chlorination making the water at times very unsatisfactory.

The contemplated Silver Creek water supply project contains the following features; A rockfill dam on Silver Creek at Union Valley, of a 74 million cubic meters storage capacity; concrete arch diversion dam on Silver Creek 42 meters high and 98 meters crest length; one 3.05 meters inside diameter tunnel 490 meters long and one similar tunnel of 6.70 kilometers length; penstocks 1,825 meters long and a power plant of 21,000 horse power in two units of impulse type; intake works at railrace and 48.8 kilometer 1,525 to 1,650 millimeters inside diameter steel flow-line laid in trench; one equalizing reservoir of 3.7 million cubic meters capacity involving a rockfill dam 42 meters high and 244 meters length on crest; enclosed pressure pipe-line 45.80 kilometers length of 1,520 to 1,220 millimeters inside diameter under a head of from 15 to 90 meters. Capacity of the upper works as far as the equalizing reservoir is 340.60 million liters daily, that of the lower system being 264.98 million liters daily. Po-

pulation tributary to the Silver Creek water supply project now totals 115,000. The project will serve an ultimate population of 250,000 expected to be reached about 1960.

A number of smaller cities and towns have planned or built new water supply systems during recent years to take care of their expected growth in population for longer or shorter times in the future. One of the more important of these is the Pine Canyon Dam and water supply project for salvaging waste flood waters of the San Gabriel River, Los Angeles County, and bringing the water to the city of Pasadena. The principal items of this project are a gravity dam, straight in plan, 73.25 meter high above streambed and 99.25 meters high above lowest foundation, a spillway equipped with automatic drum-type gates capable of discharging 1,985 cubic meters per second and a 2.27 cubic meters per second conduit line 28.50 kilometers long consisting of tunnel, steel pipe and concrete pipe. The concrete dam and reservoir, located at Pine Canyon 6.5 kilometers above Azusa, is intended for future use as a unit in the Los Angeles metropolitan water system. This dam was designed for earthquake shock with an acceleration of 0.1 g.

The city of Eureka, on the north Pacific coast of California is another community with a recently completed modern water supply system. The source of water is the Mad River, a stream about 160 kilometers long and having its headwaters about elevation 1,000 meters above sea level in the Trinity Mountains which range from 1,500 to 2,400 meters in height. The watershed is narrow but the precipitation averages about 1,275 millimeters per year, with a maximum recorded flood of 538 cubic meters per second and an average annual runoff of 863.46 million cubic meters. At a point 30.5 kilometers from its mouth in the ocean 10 kilometers northwesterly from Arcata, the river passes about 16 kilometers east of Eureka and a site suitable for an arch dam permitting a gravity supply to the city. The development consists of a variable-radius concrete arch dam 35 meters high above streambed and 40 meters above deepest foundation. The storage capacity is 24.47 million cubic meters with resulting clarifying action.

Rapid growth is characteristic of most American communities. This is especially true of those in industrial districts and in the rapidly developing Western States, such as California. The normal population growth for the average American city is 20 to 30 per cent each decade, but for the average California city it was during the last decade, 50 per cent and over. Half of the cities of the State with 8,000 or more population in 1920 experienced an increase of more than 75 per cent during the decade 1910-1920 and several of them doubled, and even trebled their size.

These phenomenal growths bring added responsibility to city administrations and water works managers. For example, it is often found desirable to design and build major structures for the ultimate supply in order to meet the requirement of economic cost. In semi-arid and arid regions where the supply is limited and there is probability of its use for other purposes, expenditures for water rights and lands become necessary long in advance of actual need. It is quite common to find large cities looking

ahead 40 to 50 years in their water-works construction programs, and, where located in regions of limited supply the acquisition of lands and water rights from 75 to 100 years in advance is not unusual (Lee, 1926).

The problem of determining the amount of water which will be required for future needs presents itself whenever any step is taken to provide additional water supply. It is the usual practice when estimating the requirements of an anticipated population to project the current rate of growth and supply per capita, the consumption based on present experience, modifying it, however, by probable changes in the character and amount of use. This method gives results sufficiently reliable for short periods and under ordinary conditions where domestic and public use predominate, or where expansion without radical change in character of use is to be expected. A growing number of communities, however, show a tendency toward increase in demands of a character that cannot readily be determined on a basis of population and per capita consumption. Among such demands may be mentioned the use of water for industrial purposes, which often represents an important part of the total draft upon a water system. There is also the increased demand for water resulting from the tendency of modern cities to extend their borders beyond the built-up limits, thus adding much land devoted to commercial gardening, as well as tracts laid out as suburban residence property. In arid and semi-arid regions such areas require much water for irrigation. The amount of water required for either industrial or irrigation purposes bears no direct relation to population, and its use as a divisor is entirely arbitrary. Many of the instances of apparent abnormally high rate of consumption are due to relatively small population and large industrial or other special demand.

Perhaps the most complex of all problems of this character, is the future water requirements of metropolitan areas. Such areas will always be composed of distinctive units, some urban or suburban residential, some commercial or industrial, and some rural or recreational. Each will have different water requirements, the amount in many cases will be wholly unrelated to the number of individuals resident upon such areas. This problem has long since come to the front in California in the metropolitan districts of Los Angeles and San Francisco, the East Bay cities, and will later arise in the metropolitan areas which are beginning to surround San Diego and other rapidly growing cities. Recreational areas such as those about Monterey Bay and Santa Barbara also have this problem to meet.

The character of raw water varies greatly. Many lake waters in their natural state, because of low movement are settling basins and can normally be expected, where not agitated, be considered ideal for furnishing potable waters, while other lake waters require treatment, especially where they are polluted by the cities located on them. The California mountain-lake waters are generally suitable for domestic use without treatment. Clean watersheds, impounding reservoirs, which are kept free from pollution and long storage of water before use, are considered the best agents for purification.

San Francisco has its Hetch Hetchy watershed and other reservoir sites

excluded from contamination and neither purifies or filters its supply; is however, installing chlorination equipment for the control of crenothrix on the Hetch Hetchy Aqueduct. The East Bay cities water system is equipped with purification plants for regular use or for use at times of possible turbidity of the stored water.

Water with sulphate of lime and magnesia have a permanent hardness that may be reduced a little with difficulty; water with carbonates of calcium and magnesium has a temporary hardness which may be largely eliminated. Hard waters demand a softening process before the proper detergent action of soap can be brought into play, furthermore, their use in boilers is undesirable because they produce boiler crust and scale by deposition of salts present.

The city water authorities sum up the advantages of a soft water; a soft water reduces the use of soap in laundries and in silk dyeing, and affects favorably the operation of steam power plants, brewing and photographic establishments. A soft water with low corrosive action eliminates, to a great extent, scale in boilers and corrosion of tubes, thereby reducing the cost of steam production and the probability of accident. The use of soft water means the aggregate savings of large sums of money in the larger cities.

Scientific investigations have subjected raw water to various processes, so that the quality of water is attaining a high degree of potability. Sedimentation reduces turbidity; sulphates of alum or iron complete this work; filtration removes harmful and undesirable bacteria; chlorination complements filtration; aeration adds oxygen which eliminates taste and odor due to destroyed bacteria; coppering aids in removing taste, and sulphates of lime and magnesium tend to remove hardness. Investigations promise an absolutely tasteless water in the future. Thus the waters of the land may be brought to the household clear, tasteless and sanitary and to the factory soft and clear.

The great problem that remains, not least in California, is the quantity of water in the face of growing populations. Systematic investigation, not of a city's possible resources, but so that a proper and satisfactory distribution of surface waters may be made without infringement of the rights of others, of the water resources of an extensive area containing many urban groups is the need of the immediate future. The re-use of water is another most important field in which research is being carried on. In this respect, Los Angeles has taken the lead in the West and the results have been most gratifying.

The present utilization of the water resources of California for public and domestic supply is in the following to be measured in terms of total volume of water, as well as in terms of aggregate urban population. Statistical values as found by the Water Resources Committee of the National Resources Board (Huber, 1935), will be used. The wide divergence in annual use will require a brief consideration of each section.

North Pacific section:—The estimated total urban population of this section aggregating 61,000 is divided among its more important cities and towns as follows:

Klamath Falls	16,100
Eureka	15,800
Santa Rosa	10,600
Ukiah	3,100
Fort Bragg	3,000
Healdsburg	2,300
Yreka	2,100
Five cities and towns having a population of more than 1,000 but less than 2,000 . .	8,000
Total	61,000

The only available record of per capita water consumption in this section is 303 liters per day for the city of Eureka. As 75 per cent of the urban population reside in areas of higher summer temperature and lower precipitation than those at Eureka, it has been estimated that the average urban per capita consumption of the section is 340 liters per day or 124.4 cubic meters per year. Water is derived both from stream diversion and by pumping from wells.

San Francisco Bay section: —The use of water as a public supply is the most important in this section. The estimated urban population, aggregating about 1,400,000 is divided among the more important cities and towns as follows:

City of San Francisco and Environs . . . 650,000

East Bay metropolitan area comprising cities as follows:

Oakland	284,000
Berkeley	82,000
Alameda	35,000
Richmond	20,000
San Leandro	11,500
Piedmont	9,300
Albany	8,600
Hayward	5,500
Two other small towns less than 5,000 and over 1,000	6,100
Total	462,000

Suburban cities south of San Francisco as follows:

Palo Alto	13,700
San Mateo	13,400
Burlingame	13,300
Redwood City	9,000
Daly City	7,800
South San Francisco	6,200
Eight other small cities less than 5,000 and over 1,000	17,600
Total	81,000

Suburban cities north of San Francisco as follows:

San Rafael	8,000
San Anselmo	4,600
Mill Valley	4,200
Five other small cities less than 4,000 and over 1,000	7,800
Total	24,600

Carried forward	1,217,600
San Jose	58,000
Vallejo	14,500
Pittsburgh	9,600
Petaluma	8,200
Martinez	6,600
Napa	6,400
Santa Clara	6,300
Twelve cities less than 5,000 and over 1,000	24,000

Total San Francisco Bay Section 1,352,100

It has been estimated (Huber, 1935), from available data that the average annual consumption of an urban population, aggregating 1,147,000 is 129.52 million cubic meters at the per capita rate of 112.93 cubic meters per year on an average of 310 liters per day.

The necessity for an additional public water supply from other than local sources being apparent, the city of San Francisco about 25 years ago initiated the construction progress necessary to bring an ultimate supply of 1,514,160 cubic meters daily from the Tuolumne River, a stream in the San Joaquin section. A portion of the requisite storage has been created and the first unit of the aqueduct, 250 kilometers in length, having an initial capacity of 227,120 cubic meters per day, has been completed and in operation.

The public water supply of the East Bay metropolitan area secured principally by the conservation of runoff from local streams and to a lesser extent by pumping from wells proving inadequate in 1924, these cities united in the formation of the East Bay Municipal Utility District. The district purchased the existing utility and secured an additional supply from the Mokelumne River, a stream in the San Joaquin section. Storage in the volume of 273.84 million cubic meters was created by the construction of the Pardee Dam at the Lancha Plana dam site, and the first unit of the aqueduct 151.5 kilometers in length, having a capacity of 189,270 cubic meters daily has been in service since 1929. A supply of 757,080 cubic meters daily may be ultimately secured from this source.

The greater part of the water supply of the city of San Jose is secured by pumping from wells. Some of the cities north of San Francisco Bay obtain their water by surface diversion from small streams as well as by pumping from wells.

Central Pacific Section:—The estimated total urban population of this section aggregating 111,000 is divided among its more important cities and towns as follows:

Santa Barbara	33,600
Santa Cruz	14,400
Salinas	10,300
Monterey	9,200
Watsonville	8,300
San Luis Obispo	8,300
Santa Maria	7,000
Pacific Grove	5,500
Hollister	3,800
Lompoc	2,800
Paso Robles	2,500
Carmel	2,300
King City	1,500
Total	109,500

It has been estimated from available data that the average annual consumption of an urban population aggregating 80,000 is 13.57 million cubic meters at the rate of 169.6 cubic meters per year equivalent to an average daily per capita consumption of 465 liters.

The cities of Santa Barbara, Santa Cruz and San Luis Obispo secure their supply separately from surface water diversions while the cities on the Monterey Peninsula, Monterey, Pacific Grove and Carmel, receive their supply from a single diversion. Salinas, Watsonville, Santa Maria, Hollister, Lompoc, Paso Robles and King City secure their water supply separately from underground sources.

South Pacific section:—The estimated total urban population of the section aggregating 2,300,000 is divided among its important cities and towns as follows:

The metropolitan area of Los Angeles comprising 44 cities:

Los Angeles	1,238,000
Long Beach	142,000
Pasadena	76,000
Glendale	63,000
Santa Monica	37,000
Alhambra	29,000
Huntington Park	25,000
Pomona	21,000
South Gate	20,000
Inglewood	19,000
Beverly Hills	17,000
Burbank	17,000
Whittier	15,000
South Pasadena	14,000
Compton	13,000
Monrovia	11,000
28 cities less than 10,000 and over 1,000	128,000
Total	1,885,000

Other cities outside the metropolitan area of Los Angeles:

San Diego	148,000
San Bernardino	37,000
Santa Ana	30,000
Riverside	30,000
Redlands	14,000
Ontario	14,000
Ventura	12,000
Anaheim	11,000
Fullerton	11,000
29 cities less than 10,000 and over 1,000	102,000
Total	409,000

Total urban population South Pacific section 2,294,000

It has been estimated from available data (Huber, 1935), that the average annual consumption of the urban population aggregating 1,494,000 is 272.61 million cubic meters at a rate of 182.47 cubic meters per capita per year equivalent to an average daily per capita consumption of 500 liters. The per capita consumption has been estimated at 757 liters per day for the less densely populated municipal areas whose domestic water service is utilized for the irrigation of large gardens.

The urban population which has increased about 700 per cent during the last thirty years is now approximately one-half of that of the State of California. This area for which a water supply has been provided has increased about 500 per cent during the last thirty years and now embraces approximately 400,000 hektares or 4,000 square kilometers. Of this area using water chiefly for irrigation, 97,000 hektares comprise the aggregate area receiving domestic and industrial service and an aggregate of 71,000 hektares is in the transition stage from an aggricultural to urban.

The annual domestic and industrial consumption in an area of 36,000 hektares in Los Angeles, having a population of 1,000,000, is approximately 209.70 million cubic meters or 522 liters daily rate per capita.

Water is secured by the intensive development and use of local sources, both surface and underground. In addition there is secured by conservation and direct flow from the Owens River in the Great Basin about 246.70 million cubic meters per year. Development now being carried out will make available about an equal amount per year from the Mono Lake area farther north in the Great Basin. It is estimated that at the present rate of growth this supply will be fully utilized by the time the water secured from the Colorado River by the completion of the 420 kilometers long aqueduct from Parker on the Arizona-California boundary is brought in.

The City of San Diego, lying in the southern end of the section, includes an area of 9,725 hektares and has a population of about 148,000. The total annual consumption is about 23.44 million cubic meters or on an average annual per capita consumption of 158.3 cubic meters or a daily rate of 434 liters.

Sacramento Section:—The aggregate population of the more important cities and towns is approximately 172,000. These with the population are as follows:

Sacramento and environs	96,000
Chico	7,900
Roseville	6,400
Marysville	5,800
Woodland	5,500
Redding	4,200
Grass Valley	3,800

Carried forward 129,600

Oroville	3,700
Yuba City	3,600
Red Bluff	3,500
18 other cities less than 3,000 and over 1,000	32,000

Total 172,400

The City of Sacramento uses approximately 30.84 million cubic meters per year which is secured by direct diversion from the Sacramento River. This is at a rate of 321.23 cubic meters per capita per year or 878 liters per day.

Other cities and towns secure their water supply mainly from underground sources.

It has been estimated from available data that the average annual consumption for the population in these towns is at the rate of 268.01 cubic meters per year or an average daily consumption of 737 liters.

San Joaquin section:— The use of water as a public supply in this section amounts to approximately 70.0 million cubic meters per annum. The aggregate population of the more important cities and towns is about 241,000. These with their population are as follows:

Fresno	53,000
Stockton	48,000
Bakersfield	20,000
Modesto	14,000
Visalia	7,300
Merced	7,100
Hanford	7,000
Lodi	6,800
Tulare	6,200
Porterville	5,300
Madera	4,700
Turlock	4,300
Lindsay	3,000
Tracy	3,800
Taft	3,400
Selma	3,000
Sanger	3,000
Dinuba	3,000
Coalinga	3,000
Exeter	2,900
Delano	2,700
Reedley	2,000
13 cities less than 2,500 and over 1,000	20,000

Total 240,600

Practically every one of these cities and towns secures its water supply from a local underground source. It has been estimated from available data that the average annual consumption of an urban population aggregating is 44.41 million cubic meters at the rate of 290.24 cubic meters per capita per year or an average daily per capita consumption rate of 795 liters.

Great Basin: The use of water as a public supply in this section amounts to approximately 11.5 million cubic meters per annum.

The aggregate population in the cities and towns within the part of the basin lying in California is approximately as follows:

Brawley	10,000
El Centro	8,400
Calexico	6,300
Needles	3,100
Five cities less than 2,500 and over 1,000 . .	7,500
Total	35,300

It has been estimated from available data that the average annual consumption of an urban population, aggregating 32,000 in the Imperial Valley in California and of Reno, Nevada, is 16.78 million cubic meters at the rate of 524.25 cubic meters per capita per annum or a daily rate of 1437 liters per day.

For other areas, on account of the scarcity of available supplies, cooler climate and greater precipitation, the average daily consumption was assumed (Huber, 1935), to be 568 liters per capita.

It has been estimated that in California there is furnished annually for public water supply approximately 812.50 million cubic meters of water to an urban population aggregating 4,319,000.

With respect to the various sections these figures have been segregated as shown in the following:

Table 7.

Section	Number of cities having a population over 1000	Total urban population	Average daily per Capita liters	Consumption Average daily total in cubic meters	Average annual total in million cubic meters
North Pacific	12	61,000	341	20,782	7.58
San Francisco Bay	51	1,400,000	314	439,880	160.55
Central Pacific	13	110,000	465	51,150	18.67
South Pacific	82	2,300,000	587	1,349,410	492.53
Sacramento	28	172,000	825	141,935	51.80
San Joaquin	35	241,000	795	191,595	69.93
Great Basin	9	35,000	896	31,348	11.44
Totals	230	4,319,000	515.4	2,226,100	812.50

III. Hydroelectric Power.

The early development of California and the west was non-industrial; therefore power was not urgently needed. Steam generated power was early used for lighting.

The first public street exhibition of electric lights and lighting in California took place in San Francisco upon the evening of July 4, 1876, the opening day of the Centennial Exposition at Philadelphia. On that evening three large French arc searchlights, operated and erected by the Reverend Joseph M. Neri, and located upon the roof of St. Ignatius College, then located south of Market Street, were exhibited to the public. The machines used to generate the current were an old French machine used at the Siege of Paris, 1871; a more modern American machine and one of Father Neri's own make. The town turned out en masse to see the light effect, which at the time seemed wonderful (Britton, 1923). Father Neri, a renowned physicist, also lectured upon and conducted exhibitions on electric lighting in the public hall of the College. At the annual fair of the Mechanics Institute and the Mechanics Pavilion in the fall of the year 1879, there was established the first commercial arc lighting in San Francisco. On June 30, 1879, the California Electric Light Company was incorporated, a plant built and operated until destroyed by fire.

Hydroelectric power development was the natural outgrowth of the hydromechanical power of the West. The growth in size of units and distance and voltage of transmission has since been phenomenal.

The first hydroelectric plant in the West was constructed at Oregon City, on the Willamette River, Oregon, in 1889, with a 20-kilometer transmission line at generator voltage. The Pomona plant in California, built in 1892, was the first long distance transmission with a step-up voltage. The Redlands Electric Light and Power Company built the Mill Creek No. 1 plant about 13 kilometers east of Redlands in 1893. This was the first polyphase transmission and used 10,000 volts (Fowler, 1923). The consulting engineer insisted upon installing a 3-phase system similar to the one being operated for experimental purposes in Tivoli, near Rome. It was only after some months hesitation that the electrical manufacturers agreed to build two 250 kilowatt 3-phase generators.

The waters of Mill Creek used for turning the impulse wheels which are connected to the generator were diverted at a point about 3 kilometers above the plant and conducted through a 760 millimeter diameter steel pipe line to the power house where they acted on the wheels under a head of 192 meters.

Later water was diverted at two other points along the canyon and two more plants constructed. The first installation at Redlands was for generation of energy at 2,300 volts, carried at like voltage on the transmission line to the city and stepped down to 110 volts wherever occasion demanded. After three years of successful operation the potential was raised to 10,000 volts and another three-phase, 10,000-volt line built to Riverside 32 kilome-

ters distant. The current from the Mill Creek No. 1 plant was turned on the arc light system in Redlands for the first time on August 5, 1893.

On Admission Day, September 9, 1895, the Sacramento Electric Power and Light Company put into operation the Folsom hydroelectric plant—the first generating plant of any size in central California. Four 11,000 volt, 3-phase circuits on two pole lines from the power house to the city of Sacramento, 35 kilometers away, supplied energy for the street railway system, lighting and incidental power. All of these earliest hydroelectric plants in California are still in operation. Today these things are on a grander scale, when we acquaint ourselves with the 40,000 kilowatt waterwheel-driven units at Big Creek with 220 kilovolt transmission lines 360 kilometers long to Los Angeles or the similar facilities from the Pit River hydroelectric plants to San Francisco Bay, now last crowned by the 15-115,000 horse power water turbines driving 15-82,500 kva waterwheel generators at Boulder Dam, transmitting the energy over 287 kilovolt circuits to the Los Angeles metropolitan area 425 kilometers away, or over 200 kilovolt circuits a distance of 650 kilometers for the Metropolitan Water District.

Within the electrical profession California has won renown for the development of high head water power plants, the transmission of electrical energy at high voltages, and the application of the technique of high voltage transmission to the economic distribution of its water powers; and in no phase of the development of the resources of California were there required more vision, courage, resourcefulness, initiative and confidence than in the harnessing and transmitting of these powers in the form of electricity throughout the length and breadth of the state. The details of the problems encountered, both economic and technical, of the many failures, the long and painstaking research, and the final solutions, would make a story that would be an outstanding exemplification of that ingenuity and resourcefulness that has been such a potent factor in the development of the West.

Today the interconnections of transmission systems provide a physical continuity of transmission circuits from the Canadian boundary on the north to the Mexican boundary on the south. This connection furnishes a continuous line from Yuma, Arizona, to a point beyond Billings, Montana, a distance of about 3,700 kilometers.

The general topography, dominated by the various mountain ranges in excess of 3,000 meters in elevation materially influence precipitation and storage, is favorable to water power development in California. The remoteness of these mountain power sources made the development of high voltage transmission essential and without this successful development the water powers would have remained comparatively useless. With growth the amalgamation of numerous small undertakings into larger systems resulted. This consolidation influenced the standardization of frequencies, the predominating being 60 cycles, which will doubtless be generally accepted throughout the West.

The great mountain ranges constitute the most important element in California's wealth of water power resources. Unlike most other sections of the country where the major power sites consists of low head devel-

opments on the large rivers, the principal plants in California comprise for the most part high head developments utilizing comparatively limited water supplies.

The mountain ranges furnish the necessary rugged topography for the physical basis of water power developments, and in addition constitute the major influence which induces the heavy precipitation to supply the streams. Moreover, the higher mountains have a far-reaching effect on the regulation of the stream flow by preserving for a time a large proportion of the heavy winter precipitation in the form of snow, later to be released by the warm summer temperatures and serving to maintain the stream flow after the rainfall on the lower elevations has been discharged.

Practically two thirds of California is mountainous. At the north the Cascade Range extends down from Oregon, terminating in the volcanic eminences, Mount Shasta and Lassen Peak. The geological nature of this area and of the lava-covered Plateau to the east of these mountains serves to produce remarkably constant flow which makes the Pit River and the McCloud River particularly favorable power streams.

South-eastward from the termination of the Cascade Range lies the mighty Sierra Nevada, forming a huge barrier 100 kilometers wide between the eastern border of the State and the Great Valley of California. At the northern end, the crest of the Sierra Nevada averages not much over 2,000 meters in altitude, but there is a progressive rise toward the south until at Mount Whitney an elevation of 4,423 meters is attained. For a distance of 325 kilometers there is no pass lower than 2,840 meters. South from this culmination there is a comparatively rapid drop in elevation to an ordinary desert range until at Tehachapi Pass the Sierra Nevada merges with the Coast Ranges.

On the western slope of the Sierra Nevada a very large percentage of California's water power resources are concentrated, along streams tributary to the Sacramento River and the San Joaquin River. Such concentration is due to the high precipitation this region enjoys, much of it in the form of snow at high altitudes, coupled with the steep gradients in the upper reaches of most streams from the Sierra Nevada. It is said of this region that the watershed area of the 10 principal streams, which constitutes but 11 per cent of the area of the State (about the area of Switzerland), contributes over 62 per cent of its water power resources.

As already noted, the utilization of water power is almost entirely in the form of electrical energy to be transmitted from its point of generation, often in most isolated mountain regions, over long, high tension transmission systems, to the point of distribution and use, at the population, irrigation and industrial centers. Naturally, the smaller, more economical and more accessible power sites, nearest the load centers, were developed first, but of more recent years, many extensive, remote and expensive projects, involving several hundred kilometers of high tension transmission lines on steel supporting towers, have been undertaken.

Geologically the Sierra Nevada is a vast granite formation interspersed with a few small areas of volcanic origin. The main fault plant of the large

uplifted mass is on the east, leaving a great escarpment forming the eastern slope of the range which results in the streams being short and very steep. The largest stream is Owens River, which flows 150 kilometers parallel to the mountain and collects the drainage from the highest section of the range. Other streams, outside the Owens Basin, which are of minor importance from water power standpoint, are the Truckee, Carson and Walker Rivers and the small Mono Lake tributaries.

The slope of the western face of the Sierra Nevada presents a very flat gradient of descent from the crest to the edge of the Great Valley, but the larger streams have cut deep canyons and have left high ridges standing, running out at right angles from the main range, paralleling the streams. The great gorges flanked by precipitous granite walls offer the most distinctive characteristic of the Sierra region. The canyons of the Kings, Kern and Merced, are most notable, but also other streams; the Feather, Yuba, American, Mokelumne, Stanislaus, Tuolumne, and San Joaquin traverse canyons of exceptional magnitude.

The ten major streams of the Sierra Nevada, just mentioned, are similar in many respects. Each is formed by two or three main branches, which give to the watershed a roughly triangular shape with apex at the edge of the valley. Originating in numerous small lakes in glacial cirques in the shadow of the main crest, the streams descend along their upper stretches on steep slopes, which gradually flatten out towards the valley. Good reservoir sites of greater capacity are extremely scarce but with other favorable factors these streams are the most valuable power streams in California.

In the Coast Ranges the principal streams have extensive tributary basins and large annual discharge, but on account of the flat gradients and the lesser height, scarcity of practicable reservoir sites, and erratic flow, they are of small value for water power. An exception is the Klamath River and the Trinity River as well as a few others in the north properly lying within the Klamath Mountains. Klamath River has been estimated capable of yielding three-quarter to one million horse power. Its near future development has been withdrawn from development of hydroelectric power.

The characteristics of the California streams are that they vary in flow with the season markedly more than elsewhere. Many streams have a low water flow of only 2 to 5 per cent of the maximum. Again the range in discharge from year to year varies. Some northern rivers range from one-half to twice the mean and southern rivers exceed this variation.

Here it seems important to accentuate the interdependence of water power and irrigation. The prevalent idea has always been that there must be conflict between the two uses, is a popular fancy fanned by demagogues and politicians. From a technical viewpoint the two uses are closely related and instead of conflict between these two major demands for water, there is a mutual relation between them for their interests are identical. Any stream, when properly developed, can be made to furnish a maximum of power and a maximum of water for irrigation and the work of one can be so arranged that they will serve the uses of the other. It is recognized that

each river is a problem by itself, the solution of which depends upon its own physical characteristics. The various items of watershed, precipitation, seasons, storage sites, tributary land areas, etc., must be taken into account and a study made in detail before a correct conclusion can be reached.

Before stating the relationship between the most important uses of water, it is appropriate also to set forth briefly the limitations that govern the use of water for power and water for irrigation. In the modern scheme of things these two uses carry equal weight, it is of equal importance to generate power as to raise food.

As in all other phases of industry the use of power is not uniform but varies with the day and with the season. The changes in energy demand over a calendar year is of extreme importance in relation of power to irrigation, first in relation to the amount of water discharged from power storages and second, in the ability of power systems to consume the energy from a power plant taking water from a storage, the primary use of which is for irrigation and the delivery of which corresponds to the irrigation demand.

The characteristics of power systems as regards the demand in the several months of the year for energy differs widely. On examination of pertinent data it is shown that all power systems have a demand for a block of energy during the summer months in excess of the average. Two California systems illustrate the extremes. One power system ranges from a minimum of 93.4 per cent of the average in March to a maximum of 108.5 per cent in June, a range of 15.1 per cent. The other power system varies from 70.5 per cent of the average in February to 126.0 per cent in July, a range of 55.5 per cent. In the case of the latter power system the greater range is caused by the agricultural country it serves, irrigation pumping in summer forming a large element in its power demand (Galloway, 1924).

As will be seen later, the summer rise in energy demand occurs at a time when the streams have fallen towards the low period and as a result, water must be released from storage reservoirs to supply the deficiency.

In the same manner as for power systems, the summer season brings a great demand for irrigation water, much of which must come from storage reservoirs, if supplied. The demand for water varies in different localities, due to the varying amounts of rainfall, character of crops, duty of water, and other similar elements. The presence or absence of storage reservoirs has something to do with the time when water is used and the amount. So far, in California, no stream has been provided with adequate storage facilities, either for irrigation or for power. In the absence of a storage reservoir the farmers naturally desire to pour a large amount of water on their lands during the time of spring floods. Hence in May and June the demand for water is greatest. With the presence of ample water in a storage reservoir to be used when required, it is probable that the demand will be lessened in the months of maximum demand.

In the following certain basic principles of development for the two forms will be emphasized in order to ascertain the relation between the two:

Power:—(a) Power reservoirs must be built well up to the summit of

the mountain ranges to obtain most energy, but with sufficient watershed above to fill them; (b) Unit reservoir costs can be higher than for irrigation due to the greater sale value of products; (c) Water must be discharged at a fairly uniform rate throughout the low water period and into the winter months when streams are often low, due to freezing of sources of water.

Irrigation:—(a) Irrigation reservoirs should be built in the lower foothills and on the main stream if possible, but high enough to serve the lands through gravity flow; (b) Favorable sites usually exist for such reservoirs and due to a number of causes, the cost is much less than for higher reservoirs; (c) Water must be discharged at rates that vary widely at different times. After irrigation ceases, the gates should be closed in order to store water for next year; (d) A power plant can usually be built at the dam of the irrigation reservoir, and the energy therefrom sold at rates that will yield substantial profit.

Proper storage reservoir sites are of utmost importance and must be pointed out as the subject does not seem to receive the attention it justly requires. It is a rare case where reservoir sites exist in the high mountains, the development cost of which is less than an equivalent reservoir at a lower elevation. The contrary is generally the rule. Again no irrigation reservoir should be built that depends upon the melting snow to fill it. The snow is a storage of water and its time of melting coincides with the time of greatest irrigation demand. The irrigation reservoir should be located in the foothills just above the gravity canal system so that it will fill from the runoff from winter rains in the foothills, or from water discharged from power storage reservoirs during the winter low water.

From the discussion so far it will be recognized that two direct benefits to irrigation follow from the construction of power storage reservoirs above the irrigation reservoirs. The size of the irrigation reservoir can be materially decreased with resulting saving in cost over that necessary if power storage is not present. The second benefit, which is much greater, is that the water stored for power in one year is carried over to the next for irrigation and thus makes more certain the filling of the irrigation reservoir.

The United States would have 57,184,000 horse power of hydroelectric power available 50 per cent of the time if all the streams were fully regulated and all possible power plant sites occupied by plants having an overall efficiency of 70 per cent, the United States Geological Survey estimated in a release to the press of August 20, 1936. In order to conform to tentative international standards, the present survey also shows the potential water power in kilowatts at 100 per cent efficiency, based on water available 95 and 50 per cent of the time and on arithmetical mean flow, without taking account of future storage.

These figures for potential power are not directly comparable with figures for developed power because developed power is customarily, and so in the latest release of the United States Geological Survey of January 1, 1937, in terms of the capacity of the installed water wheels or turbines, which usually is several times the potential power available 95 per cent

of the time. Probably with complete development of the water power of the whole country the installed capacity of water wheels and turbines would amount to 80,000,000 horse power or more. A very considerable percentage of this potential as well as installed water wheel or turbine capacity is to be found on the Pacific Slope, in the States of Washington, Oregon and California as shown in the following:

Table 8. Potential Water-power of the United States with storage in thousands of horsepower (70 percent efficiency; gross head).

	Available 90 percent of the thime		Available 50 percent of the thime	
	Horsepower	Percent	Horsepower	Percent
United States	42,753	100.00	57,184	100.00
Washington	8,768	20.51	12,021	21.02
Oregon	4,361	10.20	5,956	10.42
California	4,605	10.77	5,983	10.46

Based on the tentative international standard the values are as follows:

Table 9. Potential Water-power resources of the United States with existing flow in thousands of kilowatts (100 percent efficiency; gross head).

	Available 95 percent of the thime	Available 50 percent of the thime	Based on mean flow
United States .	25,045	58,863	82,180
Washington	4,823	11,667	18,278
Oregon . .	3,232	6,337	8,700
California .	2,765	5,624	8,461

Table 10. Total capacity of water wheels at Water-power plants in the United States January 1, 1937 (Plants of 100 horsepower or more).

	Total		Public utility and municipal		Manufacturing and miscellaneous	
	Number of Plants	Capacity in Horsepower	Number of Plants	Capacity in Horsepower	Number of Plants	Capacity in Horsepower
United States .	3,067	16,079,407	1,573	14,185,908	1,494	1,893,499
Washington .	69	1,037,134	61	988,574	8	48,560
Oregon . . .	75	360,439	49	306,509	26	53,930
California . .	140	2,444,187	118	2,425,395	22	18,792

In regard to distribution of total capacity of water wheels installed, with United States 100 per cent; the Pacific Division had 23.0 per cent of which Washington showed 6.4 per cent; Oregon 2.3 per cent and California 15.2 per cent.

Since the year 1926 California has been in the first rank among the states of the Union in total capacity of water wheels. Based on the present practice in the installation of water wheels for the utilization of water power sites, it is estimated that water wheels having a capacity of about 80 million horse power would be required to utilize all of the water power in the United States. Therefore, 20 per cent of the Nation's water power is developed at the present time. For California the developed power is 20 per cent when computed on the same basis.

Within California conditions vary greatly with respect to the physical and climatic features, and, as a result thereof in possibilities for the present and the potential development of water power. Concerning potential future development of water power in California it should be noted that the very large production of crude oil accompanied by a large volume of natural gas will have a material influence upon its economic aspects.

In the following the various sections will be briefly considered in regard to water power conditions and development to date.

North Pacific section:—This section includes all streams in California flowing into the Pacific Ocean north from San Francisco Bay. The major portion of this section is a well-forested, mountainous region that enjoys rather abundant precipitation. It is sparsely inhabited, the principal occupations being lumbering, stock raising, dairying and mining.

Klamath River is by far the most important power stream in the section. Its upper tributaries rise in south central Oregon south and east from Crater Lake, flows through Klamath Lake, where the discharge is regulated, then Klamath River finds its way through the Cascade and Coast Ranges via a tortuous canyon route where but limited opportunities for agricultural development exist. The present water power development consists of six plants of the California Oregon Power Company with a total capacity of about 60,000 kilowatts, all within 100 kilometers of the Klamath Lake. The potential water power capacity of Klamath River, alone, is variously estimated to be between 750,000 and one million horse powers.

Trinity River is the largest tributary to Klamath River, draining the western slopes of the Klamath Mountains and the Coast Ranges, joining the Klamath River 70 kilometers from its mouth. The Central Valley Project of the State of California contemplates diversion of the headwaters of the Trinity River into the Sacramento River watershed for irrigation and water power development. Mad River, Eel and Russian Rivers are the only other streams so far considered for power development. The total installed capacity to date, for the North Pacific section, is 70,550 kilowatts, with a potential capacity of 1,782,000 kilowatt additional.

San Francisco Bay section:—This section is the principal power consuming center of northern California, but has no water power production of

its own and no potential developments of merit exist, within the section (Huber, 1935).

Central Pacific:—This section embraces all streams flowing into the Pacific Ocean from San Francisco Bay to Santa Barbara Channel. While this region is quite rugged, the precipitation is not great and the summer flow of the streams is greatly reduced. There is but one small water power plant, of 950 kilowatt capacity, in the section, and, so far as is known no future developments of consequence are contemplated or possible.

South Pacific section:—This section extends from the Santa Barbara Channel to the Mexican boundary, and includes the coastal plain wherein has been developed the extensive population and industrial district of southern California, of which Los Angeles forms the center. Precipitation in this section is moderate to slight, and uncertain, though considerable snow accumulates in the higher mountains to the north and east. Although there is a great demand for power, only 18,275 kilowatts in water power units have been developed. Within this section, the city of Los Angeles has installed 104,000 kilowatts in connection with the Owens River Aqueduct, but that amount is credited to the Great Basin, where the water originates.

In addition to the hydroelectric power imported to this region from the San Joaquin section and the Great Basin, and the steam-electric power generated locally, there will be available from the Boulder Canyon Project on the Colorado River, probably 2,805 million kilowatt hours per annum, equivalent to an installed capacity of about 680,000 kilowatt. This is equal to, or greater than, the present developed hydroelectric power capacity tributary to that market, and approximately equal to the steam-electric power available in that market.

Sacramento section:—Sacramento Basin embraces that portion of the Great Central Valley of California, north of the junction of the Sacramento and San Joaquin rivers, the adjoining eastern slope of the Coast Ranges and the adjoining western slope of the Sierra Nevada. It is in this western slope of the Sierra Nevada Mountains that the greatest power resources of California exist, approximately 5 per cent of the area of California contributing 27 per cent of the runoff, and 40 per cent of the total power possibilities. The principal development to date has taken place on south Yuba, North Fork of Feather and on Pit River as well as on the South Fork of the American River. The total for these, and lesser developments, being 510,700 kilowatt, with 2,932,800 kilowatt listed as potential.

San Joaquin section:—San Joaquin Basin embraces that portion of the Great Central Valley of California south of the junction of the Sacramento and San Joaquin rivers, the adjoining eastern slope of the Coast Ranges and the western slope of the Sierra Nevada. As in the Sacramento section, it is the western slope of the Sierra Nevada that contributes the hydroelectric power resources. To date, a total of 859,850 kilowatt has been developed, while the undeveloped power is listed at 1,775,630 kilowatt.

Much of the power produced in this section is exported to the population and industrial centers of southern California and of the San Francisco Bay region.

Great Basin section:—All of California to the east of the Sierra Nevada Mountains and south-east of it lies within the Great Basin with the exception of an area draining to the Colorado River.

Much of this area is semi-arid, where the rainfall is very limited and uncertain and occurring streams come entirely from the eastern slope of the Sierra Nevada. This portion of the Great Basin has some merit for hydro-electric power production, from Lake Tahoe to Owens Lake. Most of the 193,070 kilowatt present installed capacity of the entire Great Basin has been developed in the Owens River watershed, and along the aqueduct to Los Angeles for transmission to that center of population and industry. The potential future installation in this section of California is comparatively small even considering possible storage.

The degree of efficiency now achieved in the generation of electric energy in steam power plants, located in close proximity to centers of intensive use, accompanied by very low fuel cost incident to the almost local production of crude oil and natural gas in California results in an extremely low cost per unit of power. In large central steam stations only two-third kilogram coal or its equivalent, is today required per kilowatt hour. Boiler tests show efficiencies between 82 and 92 per cent.

Remoteness of location requiring long and expensive transmission lines together with the necessity for creating costly seasonal and cyclic storage, will add to some projects otherwise meritorious, a financial burden sufficient to preclude their economic justification.

The cost of generating electric energy is only a small part of the total cost of making it available for use. Hydro power, for example, is not cheap power because of high installation costs and equally high fixed charges. At some 15 projects in the United States in which the cost per kilowatt of hydro power on an installed capacity basis varied from \$125 to \$348. In contrast, steam power costs for some 30 plants varied from \$82 to \$180. Hydro fixed charges show variations from 0.342 cent to 4.56 cents per kilowatt hour on a 90 per cent load factor basis, and from 0.38 cent to 1.067 cents on a 40 per cent load factor basis. Hydro costs are not predictable from general experience and knowledge of the art of generation, but will depend on head, topography, geology, stream flow and location.

Transmission costs for hydro power rise rapidly from 300 kilometers and with decrease of load factors below 50 per cent they approach steam power costs. In other words it is cheaper to transport fuel than electricity, especially the liquid or gaseous fuel, by pumping through pipe lines, although the exact balancing point involves local considerations. At any rate distribution cost is the major element in total cost of energy and it varies greatly with customer, use, and type of construction. Finally in hydro power development there is no trend to lower costs. On the other hand, the art of transmission has been greatly improved during the last 15 years.

The hydroelectric industry is a dominating factor in the commercial and domestic life in California. Its transmission lines silently bear the energy which make possible the various industries and give vitality to the general growth. To a large extent it has brought about the develop-

ment, not only of the cities and towns, but of the interior rural districts. It has increased the taxable wealth manyfold, and has put into use natural water power resources which abound and formerly gone to waste. The part it plays in all phases of business and home life ranks it as a primary supporting element in the economic and social welfare of the State.

The reliability of service is probably greater in the electrical industry than in any other. The power producers are required to supply the load as demanded by each customer, not as the power producers wish to supply. They must anticipate the demands to be made. There is no delaying of delivery to existing customers.

IV. Irrigation.

There is little doubt that agriculture, including irrigation, was the foundation on which practically all the permanent communities in the arid West were built. Some of these communities are still solely dependent on this factor for their existence, while others boast of additional forms of industry such as mining, manufacturing, lumbering, etc. Communities supported by irrigated lands are no doubt more stable than those subject to the ups and downs of prosperity not uncommon to other industries, and, for this basic reason public opinion in the West has defined certain preferential rights to the use of streams, placing irrigation as superior to all other uses except domestic. (Woolley, 1927.)

Irrigation in the arid West is the foundation of agriculture, and generally speaking, its future growth is commonly expressed in terms of the total runoff of streams and undeveloped areas of land. The investigations of the United States Reclamation projects has, however, disclosed the fact that "the reclamation problem is today essentially an economic and agricultural problem". Widtsoe states, "Irrigation is a complex art, involving the application of the best knowledge of agriculture, especially the relationships among soils, crops and water; of engineering, especially of hydraulics of rural economics and sociology; and the life and response of human beings under the unique conditions always prevailing under the irrigation ditch".

The tendencies in the past have been that those who were interested in reclamation and agriculture never hesitated to claim that agriculture is the basic industry; those interested in mining feel that mining is the basic industry; and the stock growers are sure that theirs is a basic industry. In each case statistics are not wanting to support the claims of the various advocates. The result has been that each one of these groups has claimed the right to the waters in the streams of the land, for all were handicapped in their operations when water, by far the most valuable natural asset, was lacking.

The increasing demand for California's agricultural products that occurred prior to 1855, was satisfied by dry farming additional areas of land each succeeding year. The expansion of the improved area in farms continued up to the year 1885. Since that time there has been only slight increase in

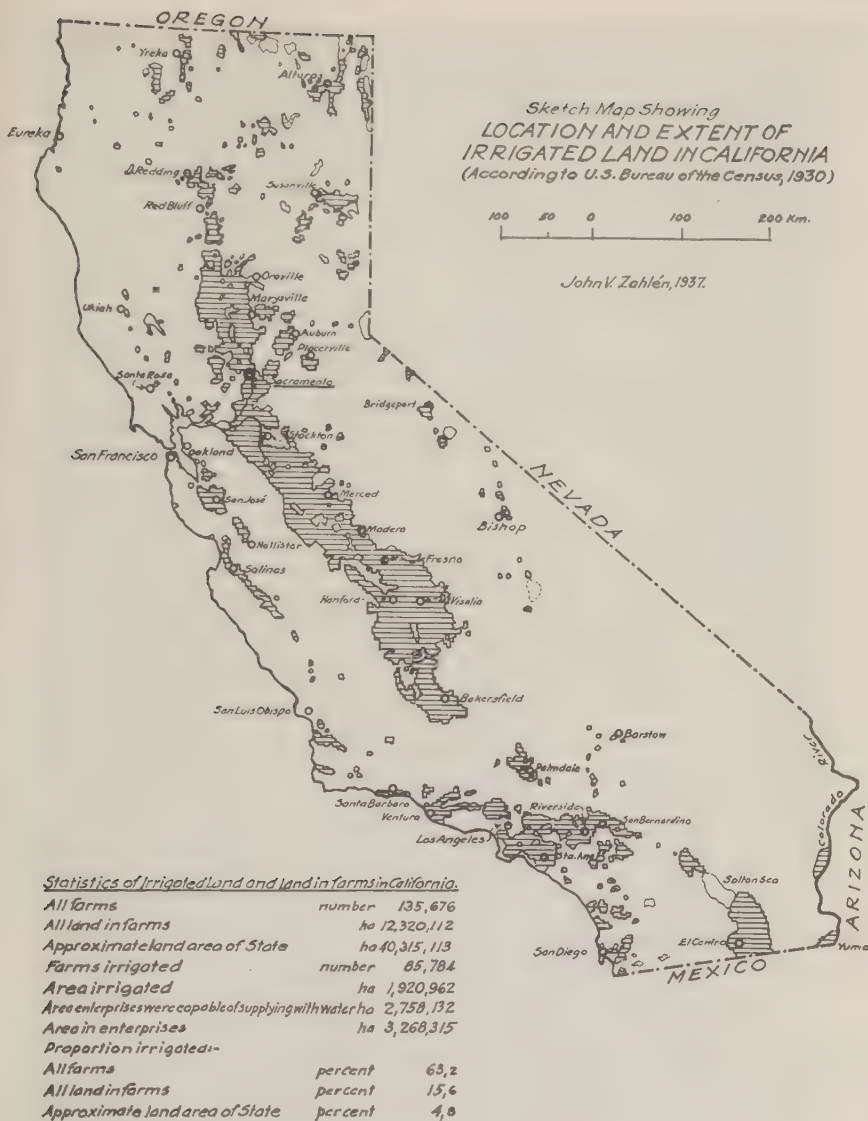


Fig. 9.

the area of the total land under cultivation. With 9,315,000 hectares of arable land in California, the extension of agriculture to new lands stopped at 4,860,000 hectares. Since the demand for the products of agriculture continued to increase, at an accelerated rate, after the expansion of the farmed area had ceased, every circumstance and condition existed for the

continuance of the extension of agriculture to new areas if it were possible. As a result of the unprofitable farming conditions obtaining on the remaining 4,455,000 hectares, the area under cultivation did not further increase. The experience of the practical agriculturist limited the total area farmed to one-half of the available area. Statistics indicate that with this area cultivated, all of the state's agricultural area with sufficient natural moisture to mature a profitable crop had been brought into use, together with some additional areas having inadequate natural moisture, but for which necessary supplementary supplies were developed.

In 1885, as we have seen, this limit to the area in improved farms was reached. Prior to this the tilled area had expanded by leaps and bounds from the great impulse given to farming enterprises that followed the world wide movement to California after the discovery of gold at the mid-way point of the last century.

During the period that this area was being brought under cultivation, 1850-1885, irrigation was practiced to some extent. As early as 1856 water was applied to supplement the soil moisture, but no great development in irrigation occurred until the early eighties, when dry farming had reached its limit (Haley, 1928). In 1885 there was less than 400,000 hectares under irrigation, while in 1900, when the phenomenal growth in irrigation expansion began, there was approximately 1,053,000 hectares under irrigation. This area has steadily increased until today there are about 2,760,000 hectares of irrigated land in California (Irrigation Census, 1930). This expansion in the irrigated area reflects the value of scientific investigation and rational application of water to the soil for growing crops, and the vital importance of water in the economical development of California is forcibly presented in the history of production of the State.

The advance of California in agricultural output has not been made by any material increase in the total area in improved farms, but rather by the application of water to areas deficient in natural soil moisture. Some additional areas having inadequate natural moisture, have since been added by developing accessory water supplies, but the abandonment of other areas previously farmed have compensated in their summation so that the total acreage in improved farms has remained nearly the same.

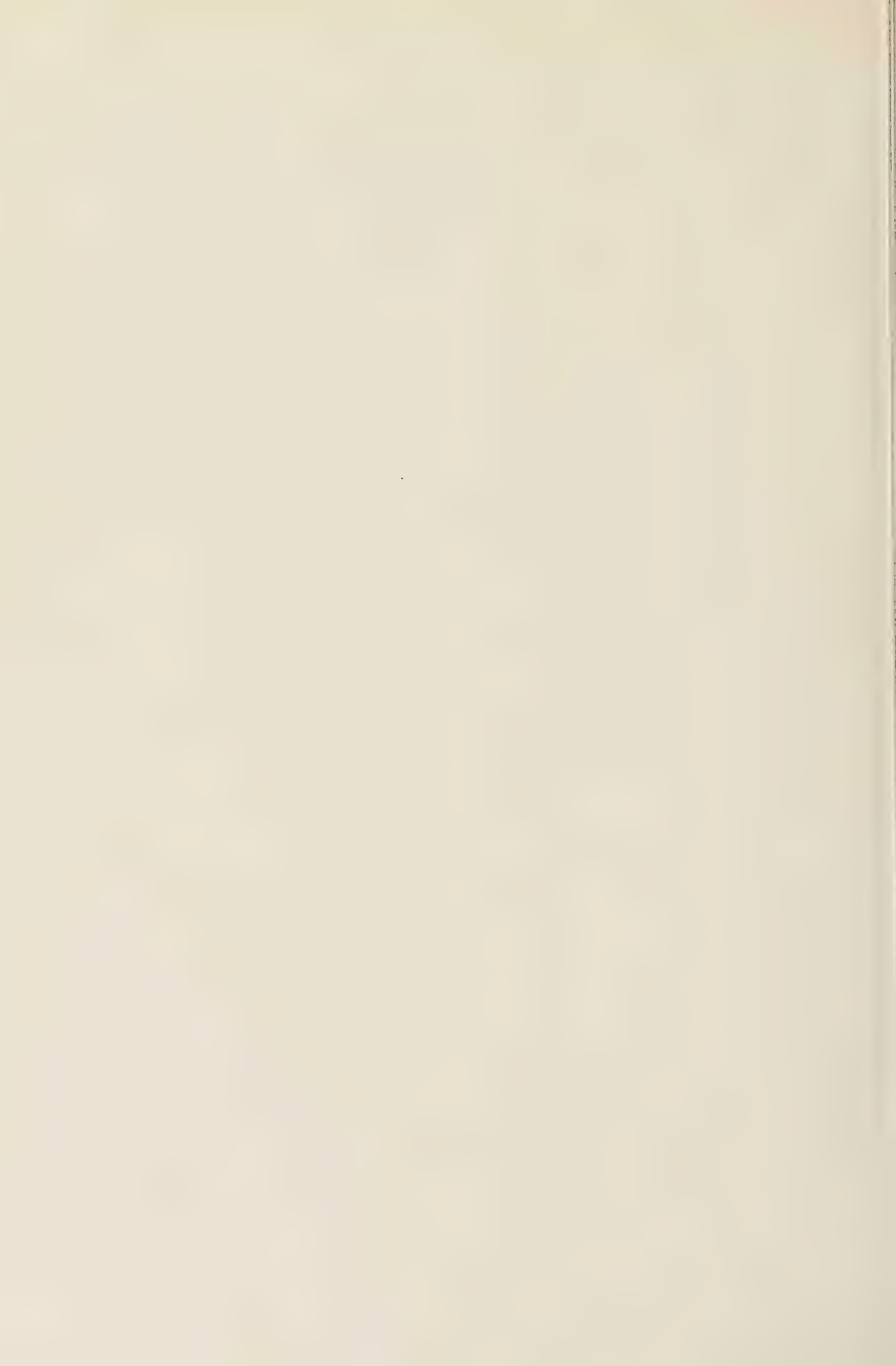
Thus it is seen that the phenomenal growth of California is not due to an increase in its cultivable area but rather to irrigation, the rational application of water to the fertile soils already farmed, to supplement the natural moisture. Through this means the soils have produced many-fold under irrigation and in this way the state has continued to respond to the constantly increased demand for its farm products.

This rapid expansion of irrigation in California has largely been accomplished through the organization of irrigation districts formed under the state, commonly known as the Wright Act, originally passed in 1887. Many amendments have been made to this act, but the fundamental objections to it were not corrected until 1897 and it was not until 1909 that the organization, development and growth of irrigation districts in California began to increase at a rapid, perhaps too rapid a rate.



San Gabriel Dam No. 1, San Gabriel River, southern California. Rockfill with impervious earth section. Highest Embankment dam in California. View shows Quarry lower left foreground. Construction shops center. Spillway excavation upper center. Outlet tunnel center lower foreground. Completed 1937.

Courtesy Los Angeles County Flood Control District



In 1933 a summary of the gross and irrigable areas of 85 districts shows the irrigated and cropped areas for 1932. The 85 districts contain 1,323,659 hectares of which 1,155,888 hectares are irrigable. The total number of holdings is 88,874 of which it is estimated 56,000 are farm holdings with a population of 225,000. Of the farm land in the 85 districts 772,118 hectares were cropped and of the cropped land 696,312 hectares or 90 per cent were irrigated. From 1931 to 1932 there was a decrease in irrigated area of 6,332 hectares.

The development of irrigation, and its related scientific technical problems which have been, and are now, playing an important part in the growth of the State is the function of the State Department of Public Works and its Division of Water Resources, under the State Engineer. In making available to the agriculturist the supplementary waters necessary for the intensive irrigation of his lands, it required the construction of diversion works, dams, reservoirs, canals and other works of such magnitude that their initial cost prohibited their being undertaken by individuals. In order to construct these works and adequately finance them it has required associated effort, which has been made possible through the California Irrigation District Act passed in 1897.

With the completion of these works, the necessity has arisen for the organization of large areas in single enterprises that overlap areas already organized in irrigation and reclamation districts. The Water Storage District Act of 1921 and the Water Conservation District Act of 1923 were passed. Resulting from the intensive studies of the water resources of California during the past 15 years is the \$170,000,000 Central Valley Project, now in its initial stages of construction.

As already stated, the agricultural lands of California comprise a total area of 9,315,000 hectares or 93,150 square kilometers. These lands are located on the floor of the valleys and in the foothills and plateaus of the state; the remainder, or three-quarters of the area of California is either mountainous with steep or precipitous slopes, soilless, too rocky for cultivation, or irreclaimable desert with barren alkaline flats and playas. Thus only a quarter of the total land area is agricultural. This comparative relation is strikingly contrasted by the proportion of agricultural lands of the whole United States where a half of the total area is agricultural. California's agricultural lands are those portions of the state that have suitable soils, disposed in appreciable areas of regular surface configuration, favorable climate and other requisite conditions for the production of harvestable crops. Included in these, are lands at present deficient in natural moisture but more or less conveniently situated for the ultimate acquisition of an accessory water supply.

The most extensive and continuous body of agricultural lands lie in the centrally located valley between the Sierra Nevada and the Coast Ranges, from Mount Shasta in the north to Tehachapi Pass in the south. This valley, the northern half of which is the Sacramento and the southern half is the San Joaquin, is 750 kilometers long and averages 65 to 80 kilometers in width, with a total area of 5,670,000 hectares of tillable land. This valley

contains 60 per cent of the total agricultural lands of California, thus the principal area of the farming area lies along the axis and in the center of the State.

The remainder of the agricultural land is distributed along the borders of the state, and in parcels that are relatively small compared to the lands of the central valley except for portions south of Tehachapi Pass. Here one-tenth of the total agricultural land lies west of the crest of the mountain range that separates the Pacific coastal plains from the desert, and one-tenth lies on the eastern side of this dividing range and principally in Imperial, Antelope and Victor Valleys; along the eastern border of California east of the Sierra Nevada Mountains, one-fortieth lies in the Valley south of Lake Tahoe, and one-twentieth in the mountain valleys north of Lake Tahoe and on the plateau's east of Mount Shasta; along the westerly border of the state; three-fortieth lie in coastal valleys of the Pacific slope of the Coast Range Mountains and between the Oregon boundary and the Santa Barbara Channel (Bull. 6).

As related to drainage and stream flow the Great Valley of California is separated into the more or less distinct parts known as the Sacramento, San Joaquin, and Tulare valleys. About 31 per cent of the total arable land lies north of the Golden Gate on San Francisco Bay, and is traversed by the Sacramento River. The remaining 69 per cent lies south of the Bay and is traversed by the San Joaquin River. Tulare valley occupies the extreme southern portion and its watershed is drained chiefly by Kern River and its tributaries. Its chief peculiarity is that in low or normal stream flow it has no outlet to the ocean, the runoff from its watershed being evaporated in shallow marshes and lakes, of which Tulare Lake is the largest. Inasmuch however, as high flood waters have spilled over into the San Joaquin Basin to the north, it is customary to consider Tulare Valley as a part of the San Joaquin Valley.

Each of the main rivers of the interior plain, the Sacramento and the San Joaquin, and Kern, not only drain the arable lands of the respective basins but an additional are of rugged non-tillable mountain land, part of which is forested.

The height above sea level of the greater part of the arable lands of California comprising the floor of the Great Valley and of the smaller valleys west of the Coast Ranges and south of Tehachapi Pass is less than 150 meters. The elevations of the rim of the Great Valley range from some hundred to about three thousand meters and more above sea level. The Klamath Lake district in southern Oregon and adjacent northern California is about 1,250 meters above sea level. As a rule, the uncultivated lands are high, ranging from low brushcovered or timbered hills to elevated tablelands and lofty mountain ranges.

The water supply of California is by far its most valuable asset, and its wise administration and rational use impose upon communities their greatest public responsibility, for water to be of value must be used from day to day as it is available. The nearest approach to conservation of water is where it is impounded in reservoirs for periods, spread over the

surface of land to replenish underground basins, or temporarily withheld by soil coverings.

One of the greatest difficulties to be overcome in dealing with water supplies for irrigation results from the fact that the precipitation and stream flow are not distributed proportionately with demands. Large areas of fertile arable land have little available water, while abundant water supplies exist in localities possessing limited areas of arable land. The transfer of the excess waters of one region to another is one of the most important problems confronting California.

In California the irrigation district, mutual company and commercial company enterprises together embrace 58 per cent of the irrigated area. The irrigation district is the outstanding type of organization, with 34 per cent of the irrigated area, and the mutual company is second with 18 per cent. Individual and partnership enterprises cover 37 per cent of the state's irrigated area, this high ratio being largely because of the extensive installation of pumping plants, especially in the San Joaquin valley.

The chief benefit in the organization of irrigation districts lies in uniting in one organization all the people of an agricultural community so that each one contributes his just share toward the expense of the enterprise, has a voice in its management and shares in its profits. It places in the hands of the landowners the management and control of the irrigation system and provides a method for securing funds to construct and operate works too costly for an individual or a small group of individuals to undertake.

An analysis of the available data on the cost of water in California, compiled cooperatively in 1930 by the (Federal) Bureau of Agricultural Engineering, the University of California, and the California State Department of Public Works, indicates that the three leading types of irrigation organizations have, in the aggregate, an important influence upon the quantities of water used in irrigation. This is due to the fact that so many of them engage in pumping, and partly to the widespread practice of charging tolls based upon the quantity of water delivered.

The mutual company is particularly important in southern California. Nearly all the leading companies in that section and many of those in northern and central California depend wholly or partly upon pumped water. The value in southern California is very high and on the whole wasteful practices are exceptional. Most of the companies deliver less than 0.76 meter depth of water, the larger quantities generally being for rice irrigation. Wasteful uses exist, but the decreasing supply of unappropriated water, the high capital costs, and frequently the high cost of operation, effectively prevent the extension and wasteful uses.

Pumping water from underground basins is practiced to a large extent. In 1930 there were 46,797 pumped wells, having an aggregate capacity of 91,866 cubic meters per minute, with a capital investment of about 240 million dollars. During the previous decade the number of plants had more than doubled due in part to a series of dry years with a resulting decrease in surface runoff and an extension of the farming area dependent

upon irrigation for production. During this time the quantity of water derived from underground sources in California steadily increased, resulting in a general lowering of the water table. In 1919 the average depth to groundwater in the state was 12.80 meters but 10 years later it was 16.20 meters. In Santa Clara County, with only a small increase in the number of pumped wells, the average ground water level dropped from 17.00 meters to 30.50 meters. Average depths of 8.80 meters in Santa Barbara County, 7.90 meters in Los Angeles County and 5.80 meters in Orange County were recorded.

In California about 607,500 hektares are irrigated by pumping from wells. A number of costs of pumping were determined in the Sacramento and the San Joaquin Valleys during 1922 and 1923, where it was found that the average cost of pumping an acre-foot (1,233.5 cubic meters) per foot height (0.305 meter), was 18.7 cents.

To counteract this increased cost of pumping an attempt has been made partly to replenish underground basins in which the lift is approaching the limit of economic pumping. This is called "water spreading", and consists in applying flood or waste water to the surface of porous soils and subsoils in such a way that it will pass through the porous material and increase the ground water supply. As a further aid to replenishment reservoirs have been built and spreading works on a large scale built below them, other reservoir sites have been surveyed and geologically investigated with the object of using stored water mainly to raise the level and increase the volume of underground water.

Spreading works are now maintained on the detrital cones at the mounths of various canyons in the San Bernardino Mountains where flood waters are allowed to percolate into the underground basins to be recovered by pumping. This method of storage has distinct advantages over surface storages, both in cost and capacity as also in the elimination of evaporation losses. This spreading practice is increasing especially in southern California and the Bureau of Agricultural Engineering of the United States Department of Agriculture has conducted experiments and made studies of spreading methods, rates or percolation, as an aid to further development of the methods.

In the following will be given a brief description of the use of water for irrigation in each of the physiographic regions of California, stating irrigated area, sources of water supply and its use also character and extent of crops produced.

North Pacific section:—Due to the great rainfall, irrigation development south of Klamath River has not made the same headway as in other sections of California. The extent of present irrigated areas are as follows; Klamath River, 76,140 hektares; Russian River 2,248 hektares; all other 607 hektares; total 78,995 hektares.

Areas in the Klamath River region are devoted to the production of dairy crops such as alfalfa and clover and also field and truck crops and some deciduous fruits. The principal planting in the Russian River area includes deciduous orchards and vineyards.

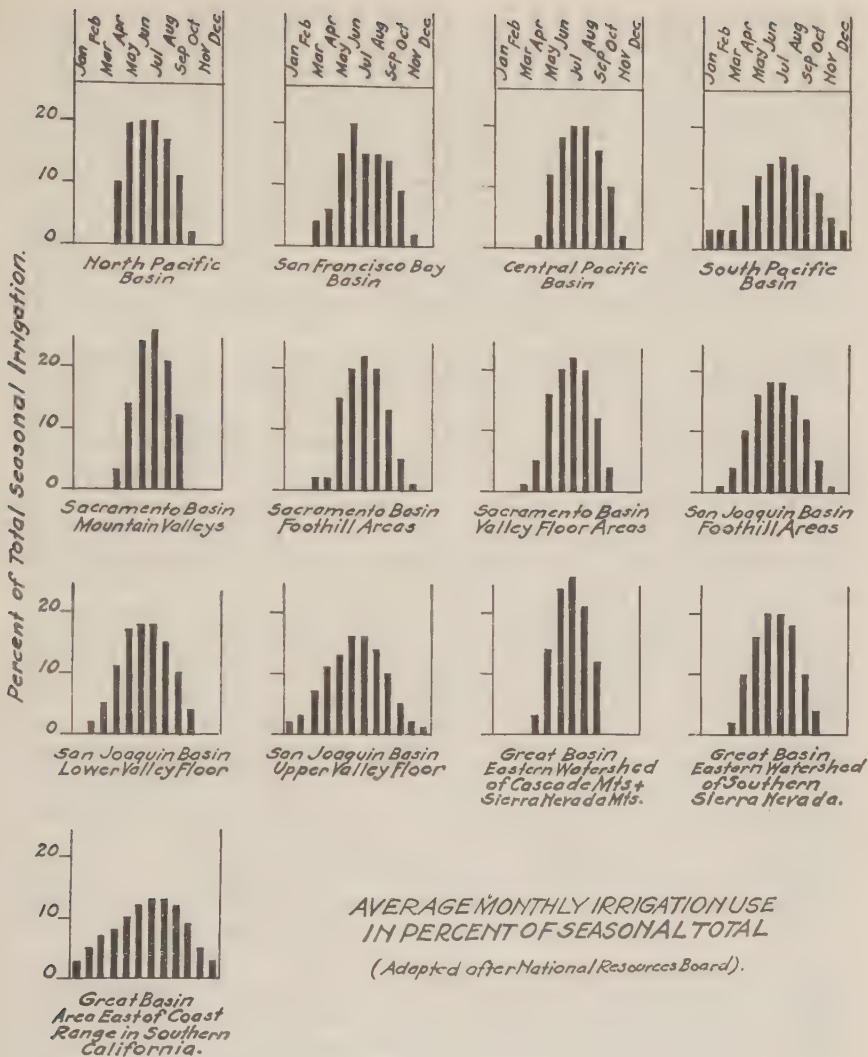


Fig. 10.

The duty of water in terms of net allowance averages 0.90 meter per annum, while in terms of net use it does not exceed 0.55 meter per annum.

San Francisco Bay section:—Rainfall in the San Francisco Bay section is greater than that in most of the agricultural areas of California and many crops can be grown successfully without irrigation. However, several large areas devoted to deciduous orchards and truck gardens are being irrigated.

Nearly all the runoff from the mountains occurs during short periods

succeeding the heavy rain storms of the winter season and no surface reservoirs are used to regulate this runoff for irrigation. Surface diversion is practiced only to a minor extent and the irrigation supply is derived mainly by pumping from underground reservoirs, which are replenished by natural percolation from the stream channels and from rain which falls on the valley floors. Irrigation applications supplement the rainfall and, therefore, are largest in seasons of low precipitation.

The irrigated areas of this section total 44,500 hektares, of which 35,400 hektares are in the Santa Clara Valley and the remainder in scattered tracts in other small valleys devoted to agriculture.

The average duty of water measured in terms of net use is estimated to be 0.46 meter per annum.

Central Pacific section:—The largest portion of the agricultural area of the Central Pacific section is in the Salinas River Valley, where the present irrigated area totals 44,500 hektares. There are approximately 8,900 hektares irrigated within the Santa Maria River watershed and 4,850 hektares in the Santa Ynez. The irrigated areas in small valleys of the minor streams aggregate about 2,450 hektares. The total irrigated area in this section is 78,975 hektares. Most of these areas are irrigated with water extracted from underground sources by means of privately owned wells and pumping plants.

The principal crops grown in the basin are lettuce, alfalfa and beans. Orchard areas include walnuts and apricots. Other plantings in order of importance are cauliflower, artichokes, sugar beets, tomatoes, carrots, potatoes, onions, berries, seeds and miscellaneous vegetables.

Due to the applied water being largely obtained by pumping from underground sources, it allows the direct return to groundwater of the excess amount applied upon the lands. Net use is the important factor in considering the water of the section. The duty of water measured in terms of net use is estimated to be 0.535 meter per annum.

About 228 millimeters of rain falls on an average during the first four months of each calendar year and little irrigation is needed until the latter half of April, neither is irrigation needed, as a rule, after the last part of September.

South Pacific section:—An area of 400,000 hektares, or about half of the net habitable area in the South Pacific section is now receiving water service. Areas totaling 237,000 hektares are devoted solely to the production of irrigated crops. Additional areas aggregating 71,000 hektares within municipal boundaries receive irrigation service but are in the transitory stage from irrigation to municipal use. The remaining water service areas totaling 97,000 hektares are those of true municipal service.

This section is characterized by the presence of absorptive formations, consisting of alluvial deposits of great depth in the valleys and coastal plains, which form large underground storage reservoirs. These furnish an unusual opportunity for re-use of return waters for municipal irrigation and industrial purposes.

In the southern part of the section, particularly in San Diego County,

there are a few absorptive areas and most of the water supply is regulated by surface reservoirs of which there are here a great number.

Irrigation is necessary throughout the entire section to secure a crop yield commensurate in value with the price of land. From the Ventura River to the Santa Ana River watershed areas, inclusive, the duty of water measured in terms of net use is 0.535 meter depth per annum. From this area south to the Mexican boundary it is 0.380 meter. Use in the latter area has been limited to some extent by the scarcity and high cost of water.

The principal irrigated areas include 96,500 hektares of citrus fruits; 86,000 hektares of field crops, 40,500 hektares of deciduous fruits and nuts; 13,800 hektares of alfalfa; 8,100 hektares of truck crops; 3,450 hektares of avocados and 2,250 hektares of grape vineyards.

The total water service area in this section aggregates 400,000 hektares and the total water consumption is estimated to be 2,072 million cubic meters per annum.

Sacramento Valley section:—The principal use of water in the Sacramento River Basin section is for irrigation. The present irrigated areas include 223,000 hektares on the valley floor, 26,800 hektares in the Sierra Nevada foothills and 56,000 hektares in mountain valleys, to which has been added an area of 130,000 hektares in the Sacramento-San Joaquin delta. The irrigated area in the basin aggregates 436,000 hektares.

The irrigated crops of the section include, citrus fruits and olives, deciduous fruits or practically every variety, nuts, grapes, hops, alfalfa, field and truck crops, cotton and rice. The irrigation supply is mostly from natural stream flow. The irrigated foothill areas are served chiefly from the Sacramento, Feather, Yuba and American rivers. Irrigated areas on the west side of the Sacramento Valley receive their water supply chiefly from the Sacramento River. The valley lands east of the Sacramento River are irrigated from the Sacramento, Feather, Yuba, Bear and American rivers and to a limited degree from small tributary streams and ground water. The Sacramento-San Joaquin delta consists chiefly of reclaimed swamp and overflow lands. Irrigation water is obtained from the channels adjacent to the various tracts either by pumping or siphoning and a large part of the area is sub-irrigated naturally.

Duty of water as measured in terms of net allowance averages 0.76 meter in depth per annum in the mountain valleys, 0.61 meter in the foothill areas and 0.76 meter on the valley floor; measured in terms of net use, it is 0.55 meters in depth for mountain valleys, 0.45 for foothill areas and 0.61 for the valley floor.

It is estimated that during the irrigation season, the total net use of water for all demands in the entire delta area will average about 0.80 meter in depth, and that the duty of water measured in terms of net use for irrigation only, will average about 0.70 meter in depth per annum.

San Joaquin Valley section:—Irrigation development in the San Joaquin River Section has been rapid and extensive, particularly in the last 30 years. The area increased from about 325,000 hektares in 1900 to about 910,000 hektares at the present time. This is more than one-third of all

the irrigated land in California and about two-fifths of the entire net area susceptible of irrigation in the San Joaquin valley section.

The irrigated crops, comprising about 80 per cent of all crops produced in the section, include citrus and deciduous fruits, nuts, olives, grapes, grain, alfalfa, practically every variety of field and truck crops, cotton and rice.

In the upper San Joaquin valley, the present net irrigated areas aggregate about 485,000 hektares. This total is made up of lands served by surface water diversion only, those served from underground sources only and those served jointly from both sources. None of the streams tributary to this portion of the section are regulated by surface storage, and the limit of utilization of their surface runoff has long since been reached.

The extent of irrigated areas dependent upon a supply pumped from groundwater has been increasing rapidly even though the ground water levels have been receding steadily. In some areas lacking adequate sources of groundwater replenishment, underground supplies either have become exhausted or ground water levels have dropped to such an extent that pumping lifts are now excessive. From the known extent of recession it is estimated that of this total 485,000 hektares, areas highly developed and aggregating 160,000 hektares are overdrawing the underground supplies naturally available to them. These areas are located chiefly in the Chowchilla, Fresno, Kaweah, Tule, Kern and intermediate minor stream areas.

It is estimated that the average annual replenishment to the underground water supply of this area of 160,000 hektares is sufficient only to provide a continued supply for about one-half of the present total or for 80,000 hektares. Therefore, an additional and foreign source of water supply must be secured, if the total irrigable area is to be maintained.

In the lower San Joaquin valley, a large area above the mouth of Merced River, chiefly on the west side of the San Joaquin River, including about 125,000 hektares of land devoted to crops, is irrigated from the San Joaquin River through diversion near Mendota. Lands receiving irrigation service in districts on the east side from the storage developments on the Merced, Tuolumne and Stanislaus rivers have a gross area of 250,000 hektares of which net areas aggregating 170,000 hektares are now irrigated.

Irrigated areas in the lower San Joaquin valley exclusive of San Joaquin delta, total about 335,000 hektares. Groundwater use for irrigation in the lower San Joaquin valley occurs mainly in the north end of the east side of the valley, chiefly in the Consumnes, Mokelumne, Calaveras and intermediate minor stream areas.

Duty of water measured in terms of net use as applicable to these areas has been estimated as follows: upper San Joaquin valley 0.61 meter; lower San Joaquin valley 0.55 meter; foothill area 0.52 meter depth per annum.

Great Basin section:—The principal use of water in the part of this section lying within California is for irrigation. Most of the present irrigation is from surface diversions with some regulatory storage. In years of plentiful supply large amounts of water, some of which are in excess of irrigation

requirements, are diverted. In years of small runoff, irrigators do not receive sufficient water to meet their needs. The California areas are approximately as follows:

(1) Eastern watersheds of Cascade and northern Sierra Nevada ranges, including the various Lake groups in the extreme north-east of California with an aggregate area under irrigation of approximately 43,500 hectares. The average duty of water in terms of net use is estimated as 0.50 meter in depth per annum.

(2) Eastern watersheds of southern Sierra Nevada, including Truckee River, Mono Lake group and Owens River. The average duty of water in terms of net use is estimated as 0.90 meter in depth per annum; irrigated area about 67,000 hectares.

(3) Area east of the Coast ranges in southern California, including Mojave River, Antelope Valley group, Whitewater River (Coachella Valley) and Imperial Valley.

The total irrigated area in this section is 210,000 hectares of which 172,000 hectares are in the Imperial Valley and receive a water supply imported from the Colorado River. An average exceeding 1.53 meters in depth per annum is delivered to the Imperial Irrigation District, and surface drainage is required. The average duty of water measured in terms of net use over the entire section is estimated as 0.90 meter in depth per annum.

In the Imperial and Coachella valleys the principal crops are alfalfa, corn, grain, cotton, mellons, vegetables and grapes with some citrus and deciduous fruits. The date industry has become prominent in Coachella Valley and the northern part of Imperial Valley.

The irrigated areas in each section, source of supply, net allowance, net use and their percentages of surface diversion water, and water from underground storage extracted by pumping, is as follows:

Table II.

Section	Irrigated area in hectares	Source		Net Allowance in million cubic meters	Source		Net Use in million cubic meters	Source	
		Surface Diver- sion %	Under ground %		Surface Diver- sion %	Under ground %		Surface Diver- sion %	Under ground %
N. Pacific . .	78,975	97.5	2.5	217.909	98.0	2.0	430.898	97.3	2.7
S. Fransico . .	44,550	1.0	99.0	203.531	1.3	98.7	203.531	1.3	98.7
C. Pacific . .	78,875	5.0	95.0	431.702	5.6	94.4	415.696	5.0	95.0
S. Pacific . .	307,800	19.7	80.3	1,578.905	18.6	81.4	1,578.906	18.6	81.4
Sacramento . .	435,780	81.0	19.0	3,268.828	82.9	17.1	2,713.744	81.8	18.2
San Joaquin . .	823,770	64.0	36.0	5,859.220	68.3	31.7	4,934.080	65.0	35.0
Gr. Basin . .	320,500	94.0	6.0	4,012.794	95.0	5.0	2,767.441	92.5	7.5
Totals	2,090,350			16,072.889			13,044.296		

V. Flood Control.

In the same measure as the progress of man goes on, growth of industry and extension of agriculture that accompanies increase in population, improvements encroach upon new lands before unoccupied. On areas of recent encroachment, attracted there by the superior fertility of the farming lands, by the valuable timber resources of the forests, the minerals in the ground, man is now waging a contest with the waters of nature for occupancy of large areas of low lands of fertile soil along the rivers, in the valleys. The conflict, more hazardous in not being continuous, rages at irregular intervals of time, and often several entire seasons pass with man and his works left in possession of these areas, undisturbed by floods. But always, though at intervals, great floods occur from climaxes of precipitation, and these waters, too great to be confined between low banks of the stream channels renew the strife with man for occupancy by threatened overflow of these land areas. In the contest for occupancy of these areas, dikes have been constructed of great length to stem the overflowing waters; river channels have been enlarged, their winding courses straightened, relief channels excavated, and various works built to prevent them from spreading out over the adjacent low areas in the way of the past. In the more advanced communities, these works protect the fields and orchards and on the fertile soils have to dwell an ever-increasing population, with good roads inter-connecting all.

Secure in having successfully withstood floods, these regions are nevertheless imperiled at times by the rise of waters to heights but rarely experienced, for the occurrence of floods, and their size and duration, are the resultant of varying sequential combinations of weather occurrences which produce at their climax, precipitations of unusual intensity or of continuance for protracted periods of time. The chance that precipitation-producing events occurring over large areas will unite or occur simultaneously to produce great storms becomes smaller and smaller as the storms become greater. For these reasons the waters of flood-creating storms pass down the stream channels less frequently as their volumes increase, for generally the magnitude of floods corresponds to the magnitude of the storms producing them.

However, to further complicate the occurrence of conditions that increase the volume of flood waters, the portion of the precipitation shed to the stream channels is not alike for all streams. The absorbency, the perviousness of the surface-covering of the watershed at the time of the storm is most important in determining the magnitude of the stream flow. Often heavy storms have such a large fraction of their waters used in wetting the catchment area, that they do not contribute excessively to stream flow. It is only when the soil, already wet to saturation or when the surface of the ground is frozen, that all of the rainfall reaching the surface of the ground runs off to the waterways. If falling, instead, on a dry soil or on an absorbent ground surface of porous structure, the interstices of which is not already filled with water, large portions and sometimes all of the precipita-

tion are taken up by the soil covering and little or none reaches the stream channels to produce floods. In other instances, when warm rains fall on snow-covered regions, the rain-water may be joined by melting snow to further swell the rising streams and a volume of water may pass down the channels greater than the entire rainfall. These conditions of the surface covering at the time of the storm, favorable or unfavorable to shed the storm waters, are largely resultant from previous weather happenings in the locality so that to produce large floods, the preceding weather occurrences must not only coordinate to make heavy downpours, but must also coordinate to render the surface on the collecting area capable of quickly turning off nearly all the water it receives. The simultaneous culmination of weather conditions on the drainage area favorable to large and rapid runoff, may be reached in all conceivable degrees of value and so result in floods varying in severity and frequency of occurrence between equally wide limits.

Floods, then, are caused by high rates of runoff resulting from heavy rainfall, melting snow or a combination of the two. The rate of runoff of a watershed is affected by the amount and intensity of the precipitation, stored water in the form of snow *nevé* or ice, temperature, size and shape of watershed, geology and soils, topography, vegetative covering and the degree of saturation of the watershed at the beginning of heavy rainfall or rapid melting of snow *nevé* or glacial ice.

The influence of each of these various factors upon the rate and volume of flood flow makes a very complex relationship, which varies greatly on different watersheds. In planning flood control improvements the engineer, in cooperation with other specialists concerned in watershed improvement, must evaluate the effects of these factors on the watershed upon which he is working, and determine the amount of runoff that may be expected, how much must be disposed of as flood water. Of the factors affecting runoff, only three of the above named can be modified by man: (1) the type of vegetative cover can be controlled; (2) the degree of saturation can be influenced by drainage works; (3) the topography is modified in some degree by erosion and by flood-control works.

Floods can be modified or controlled by (1) channel enlargement or improvement to increase capacity; (2) levees to augment channel capacity; (3) reservoirs to store water until the flood crest has passed; (4) erosion control-works and vegetative cover to retard flow into stream channels.

Reservoirs to be effective must be so located that they will retard sufficient runoff from the area above that to be protected to enable the water channels to carry the remaining flood flow without damage to the protected area. In the past it has often been assumed that reservoirs for flood control must be used exclusively for that purpose—that it was not feasible to construct a reservoir for flood control and at the same time use it to store water for irrigation, water power, recreation or domestic supply purposes. In recent years it has become apparent that frequently, especially in connection with larger water projects, by careful planning of operation a part of the storage available can safely be used for purposes other than flood control.

Dikes or levees are frequently used to confine the flood flow in a comparatively narrow floodway through the bottom lands of a stream. On most large streams a large increase in capacity is often obtained more cheaply by the use of dikes than by enlargement or straightening the channel proper. The improvement and enlargement of stream channels to control floods is usually limited to comparatively small streams or watersheds. The amount of runoff from large watersheds is so great that the cost of constructing channels to carry all flood runoff is prohibitive. Channel improvements are frequently made in connection with the use of reservoirs and dikes to reduce the size required for each improvement. Clearing streambanks of obstructions and smoothing them or lining them with concrete or other kind of paving material reduces the friction of the flowing water and often materially increases the channel discharge capacity.

The flood flow of California streams has been fully studied and tabulated (Bull. 5). It has been shown for instance that the expectancy of a flood on the Sacramento River at Red Bluff, having a volume exceeding 7,000 cubic meters per second, is four times in a century; of one exceeding 8,500 cubic meters per second, is one in a century; and a flood exceeding 9,350 cubic meters per second has an expected occurrence of but once in two hundred years, and that still larger volumes may flow down the channel at average intervals of time larger than this.

In general, it has been shown that floods will occur once in four years in more than double the size that is not exceeded on an average more often than once a year; more than treble this volume once in twenty years; and at intervals of a few thousand years may be expected in at least quintuple the volume which is exceeded not oftener on the average than once yearly.

The flood flows in California streams occasionally reach enormous values especially when the precipitation comes in the form of rain. One of the largest floods of recent years occurred during the period of March 22-27, 1928, will be noted in some detail. The six-day storm of great intensity produced new flood flow records from a number of high watersheds of the Lake Tahoe region in the central portion of the Sierra Nevada Mountains. Coming at the end of a protracted dry period in a year of subnormal rainfall and toward the close of the precipitation season, the storm was as unexpected as its results were disconcerting.

Ordinarily in the high altitudes the precipitation of the heavy storms is in the form of snowfall, but in this instance temperatures during the early part of the storm were unusually high and the warm rain carried away much of the winter snow pack, causing the unprecedented floods. Toward the end of the storm the weather turned colder and the rain changed to snow, replacing much of that which had been lost. The total precipitation for the storm ranged from 380 to 500 millimeters over the higher altitudes. In three instances unit rates of discharge exceeding 2 cubic meters per second per square kilometer were recorded. Two of these are for relatively small drainage basins and not of great importance. The discharge of 2.21 cubic meters per second per square kilometer at Lake Spaulding in 2,000 meters elevation, however, is remarkable. This rate is not large in comparison with

flood yields in some other localities, but for a high basin of the considerable size of 223 square kilometers in the high Sierra it is beyond all precedent.

The highest rate of runoff observed previously in the 25 years or more of definite records of any Sierra Nevada station above the foothill altitudes was 1.04 cubic meters per second per square kilometer at Downieville in 960 meters elevation on the North Yuba River, during the flood of May 11, 1915. The tributary area at this station comprises 184 square kilometers of territory somewhat lower in altitude than the South Yuba River above Spaulding.

At Bullards Bar Dam, on the North Yuba River, the flood conditions were also extraordinary, with a record of 1.28 cubic meters per second per square kilometer for the large watershed of 1,260 square kilometers. The flood flow on the American River was estimated to have been larger than any that has occurred since 1862. On the Mokelumne the flood was probably larger than any during the 23-year period of record on that stream. On the Stanislaus conditions were apparently about equivalent to the flood of 1907. On the watershed tributary to Lake Almanor the runoff was slightly less than in 1907, but in the Butte Creek it was higher. As in this flood the peak flow from the upper Sacramento was less than in 1907, and this combined with the fact that maximum discharge from Feather, Yuba, and American rivers failed to combine simultaneously, resulted in an aggregate flow in the lower channel considerably below the 1907 record, so that the flood protection system was not taxed to capacity (Bonner, 1928).

Turning to southern California and examining a topographic map of the Los Angeles region, we find an area of more than 10,000 square kilometers, 96 kilometers measured east and west and 110 north and south, and intersected by the Sierra Madre range running east and west into two distinct and widely different areas. In the range are peaks up to 2,700 meters in elevation. To the north of it are the broad plains of the Mojave desert and to the south fertile lands, and numerous cities and towns, of which Los Angeles is the largest, extending to the ocean. Los Angeles city's original limits as incorporated April 4, 1850, took in four Spanish leagues or about 70 square kilometers. Of subsequent inclusions, that of the San Fernando addition, with about 440 square kilometers in area, was the largest so that the city now takes in over 1,000 square kilometers and includes a narrow addition connecting it with its harbor at San Pedro.

The streams running from the north slope of the range are few, but are fully developed for irrigation on a limited area, formerly desert land but with water, yielding such fruits as pears, apricots, etc., of excellent quality.

The major streams flow from the south slope of the mountains which have in times past washed down the alluvial fill that comprises a large portion of the area. Here almost every variety of fruits and vegetables is successfully grown on the most fertile soils.

The two largest drainages fed by numerous mountain streams are the Los Angeles and San Gabriel rivers, flowing to the Pacific Ocean. During the summer season these streams present the appearance of broad boulder-strewn Wadi-stream beds, giving mute evidence of the torrential and

violently destructive occasional floods. The larger stream, the San Gabriel, has years of record floods varying from 12 millions to 675 millions of cubic meters from its 725 square kilometers of mountain watershed, while the Los Angeles has experienced years of no runoff to periods when over 370 million cubic meters was discharged from the 406 square kilometers of drainage area.

All records for short period rainfall were broken on the watershed of the San Gabriel River, during April, 1926. The Los Angeles County Flood Control District maintains automatic recording gauges on the watershed of the river, which is 518 square kilometers, divided about equally into East and West Fork. On the West Fork there are two gauges at Opid's Camp, elevation 1,200 meters. On April 5, at 4: 48 A.M. one of these gauges registered a rainfall of 24.5 millimeters and the other 25.9 millimeters for one minute intervals. A rainfall of 124 millimeters in 2 hr. 40 min. occurred between 2: 20 and 5: 50 A.M. April 5, and a total of 606 millimeters for the storm from 11: 30 A.M. April 14, to 2: 00 P.M. on April 17, making a total for the season of 1,205 millimeters.

Considerable damage from slides and material coming down the canyon occurred. Denudation of the watershed of trees and brush by fires has increased peak flows in the river. In following up such streams as the San Gabriel the visitor is struck by the sudden transition from the level valleys to the steep canyons, at the mouth of which are the large boulder-washes.

The floods bringing down large quantities of debris and silt from the mountains have wrought havoc, loss of life, and heavy losses to the fertile fields, and much time, thought and money have been expended on their control for the protection of the lands of the state, its communities and population.

The present state of protective works against floods will be briefly sketched. Works of this character generally comprise:

(a) The improvement of natural channels, affecting alignment, grade and cross-sectional area. (b) The construction of artificial outlet channels and appurtenant controls. (c) Dikes or levees. (d) Detention storage or regulatory storage devoted primarily to decreasing peak rates of flow.

The flood control works provided in the various sections are as follows:

North Pacific section:—On Lost River, a tributary of Klamath River, two reservoirs have been developed primarily for conservation, namely Clear Creek Reservoir in California and Gerber Reservoir in Oregon.

No works of any extent have been built primarily for flood control on any of the lower streams of the section. Due to mountainous nature of the lower watershed areas and the sparse settlement, such floods as do occur cause little damage.

San Francisco Bay section: Floods in the San Francisco Bay section have intensities as great as in most parts of California but are generally of short duration. The streams have steep slopes and adequate channel capacities and small overflow areas. No flood damage of any consequence has occurred and no flood control works have been established in the section.

Central Pacific section:—No large areas are subject to damage by over-

flow in this section although large floods of short duration do occur. Certain low areas are inundated in the Salinas Valley during high flood periods. Smaller flood flows are absorbed by charging the wide sandy stream channels and the large coarse gravel underground reservoirs of the basin.

South Pacific section:—The water problem in the South Pacific section is two-fold, the conservation and use of its water resources, and second, the control of floods. As shown do large storms occur in this section. Although the average seasonal water production of the mountainous region is only about one-fourth as much as in other areas of California, the rains of this section concentrate at times to produce floods equal to or greater than those from equal drainage areas of most California streams. The problem of flood control has involved the construction of various combinations of flood control works, including detention reservoirs, dikes, revetments and bypass flood channels. Conservation and flood control works have been combined in many instances. Detention reservoirs are used to retard and reduce the flood flows so that these waters may sink into the underground storage basins through constructed spreading works and natural channels.

The Los Angeles County Flood Control District has constructed 17 reservoirs primarily for flood regulation, on the San Gabriel and Los Angeles river tributaries. These reservoirs have large aggregate capacities in spite of unfavorable topographic conditions for constructing surface reservoirs of large individual capacity, located as they are in narrow canyons, on steep stream slopes. Flood channels have been improved on the watersheds, débris, dams and spreading works have been built in the upper Santa Ana Valley for retarding flood flows and charging the coarse gravel groundwater reservoirs of the region.

South of these streams, in San Diego region, no large areas are subject to damage by overflow although floods of like magnitude occur. No major works have been constructed primarily for flood control with the exception of a short diversion dike on the San Diego River. Conservation reservoirs, however, aid, to a limited extent in the control of floods.

Sacramento River section:—Previous to agricultural development in the Sacramento Valley, a large portion of its floor, including the lands in the Sacramento-San Joaquin delta, was subject to annual or periodical overflow by flood waters from the Sacramento River and its tributaries. This great flood plain, irregular in outline and of varying width from about 3 to 65 kilometers, extended from the mouth of the Sacramento River almost to Red Bluff, a distance of about 240 kilometers and comprised an area of land exceeding 400,000 hectares. A large portion of this flood plain was covered by a dense growth of tule. Surrounding the tule lands and adjacent to the river channels lay higher belts of overflow lands known as the "rim-lands". With the advent of agricultural development in the valley, these rim-lands were first taken under cultivation, being less often flooded and more conveniently located to water transportation. Here, also, flood control works were first installed along the banks by the farmers to protect their crops.

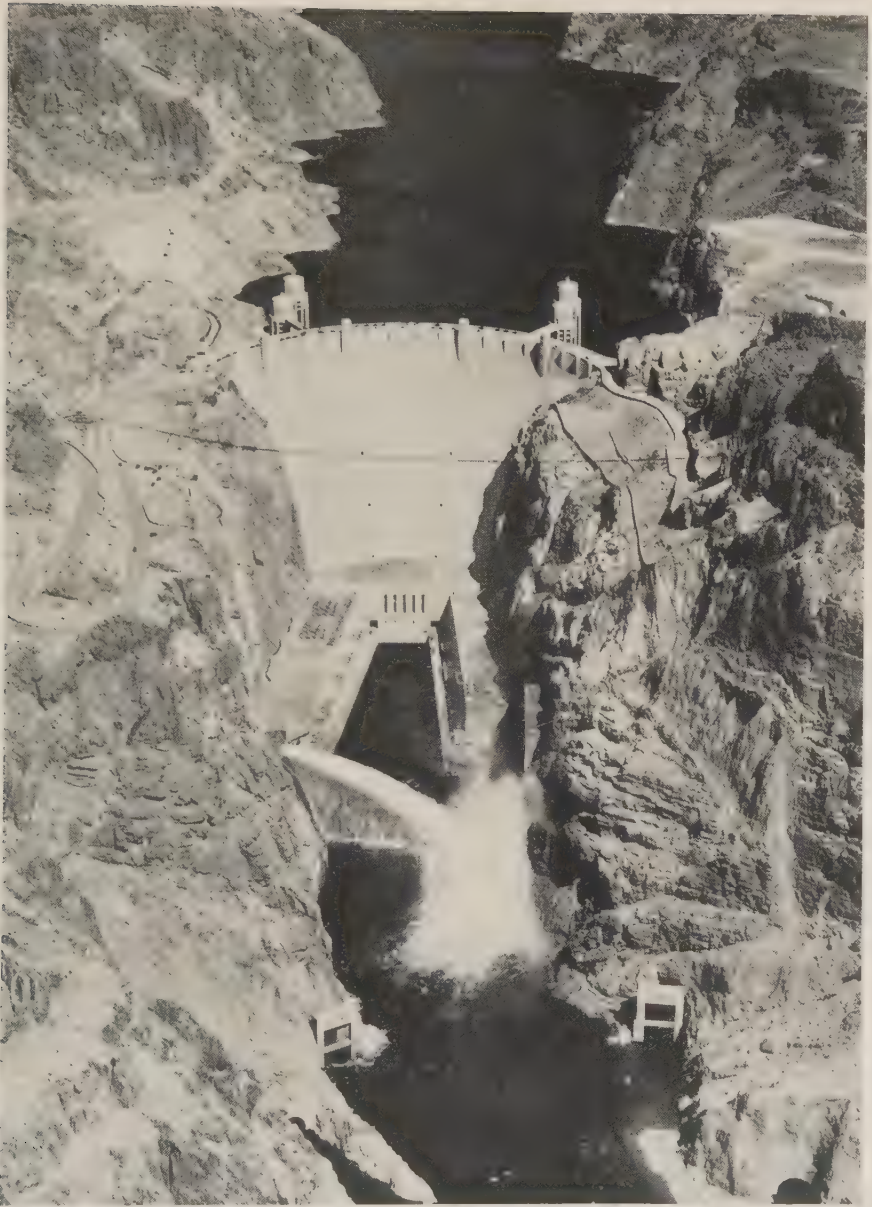
Between 1850 and 1870 most of these tule lands passed from government into private ownership. By 1894 dikes had been extended for long distances and some of the more favorably located lands had been formed into districts around which dikes were constructed. With each additional area thus diked, the degree of protection decreased for it and all other areas due to increased height of flood planes. Flood control problems were intensified by aggrading river channels, by the washing down of recurrent floods of many millions of cubic meters of hydraulic mining debris from the mountains. Already about 1884, hydraulic mining had practically ceased by court order. Investigations and reports were made dealing with reclamation, debris and flood control problems. The United States Congress became interested in the conflict between agricultural and mining interests and occasionally appointed commissions of Army Engineers to survey and evolve a satisfactory flood control and channel improvement plan.

Through this plan, carried out jointly by private agencies, reclamation and levee districts and Federal and State governments, provision is made for dikes along the Sacramento River channel, levee bypasses through the Sutter and Yolo basins; dikes along the Feather, Yuba, Bear and American rivers; various bypasses from the Sacramento River channel, from Rio Vista to its mouth. The project is estimated to be about 85 per cent completed (Huber, 1935).

The Sacramento-San Joaquin delta comprises low marsh areas, consisting of peat and alluvial soil, which in their natural condition, were subject not only to inundation from flood waters but also to tidal overflow, since much of the area is below sea level. Practically all the delta lands have been brought within dikes, which provide about the maximum degree of protection that can be obtained by this method of flood control. The dikes have been gradually built up to the limiting heights that their unstable foundations will support. Although the delta channels are many, their total flood carrying capacity is far less than the amount they may be called upon to carry in a season of major flood occurrence.

San Joaquin River section:—Under natural conditions, an area of 708,750 hectares of land in the San Joaquin section was subject to inundation by floods. About half of this area has been protected in varying degree by flood control works, chiefly comprising dikes, almost entirely constructed by local interests with only such assistance from Federal and State governments as was incidental to the improvement and maintenance of navigation on the lower reaches of the streams within the delta region. No general plan of flood protection has been adopted in the San Joaquin valley and more adequate protection is needed in many of the areas now practically unprotected from floods.

The larger areas subject to inundation in the upper San Joaquin Valley lie south of the ridges between the San Joaquin and Kings rivers. The connecting channel is Fresno Slough which joins the river at Mendota. Flood waters in this part of the valley are contributed almost entirely by the Sierra Nevada streams. Flooding in the delta areas of the streams, however, is of short duration and practically no dikes have been constructed



Boulder Dam, Black Canyon, Colorado River, Nevada-Arizona. Height above river-bed 178.7 m. Crest Elevation 375.76 m above sea level. Lake Mead Storage, Length 190 Km, Capacity 37.62 cubic Km. Power Plant, Installation 15—82,500 Kw. Main Units. Average Head 161.5 m. Completed 1935.

Courtesy United States Bureau of Reclamation, Washington, D.C.

except in the Kings River delta and around Bakersfield. Tulare Lake, lying to the south of the Kings, Keweenaw and Tule rivers, receives all waters from these rivers which are not diverted for irrigation or absorbed into the underground basins, except the amounts which reach Fresno Slough. Some water is also diverted from Kern River.

The lake has covered an area varying from nothing in dry cycles to about 1,790 square kilometers in 1862. A large percentage of the area subject to inundation in the Kings River delta and the bed of Tulare Lake is now included in organized reclamation districts having an aggregate area of about 95,000 hectares within dikes which give varying degrees of protection. In wet periods, however, much of the land within the dikes becomes inundated. The land in the lowest portion of the lake bed has the smallest degree of protection. Since 1920 Tulare Lake has been dried up or practically so. Due to heavy rainfall during the last seasons with accompanying large runoff the Lake has again increased in size until it, in the spring of 1937, measures about 25 kilometers in length by a maximum width of approximately 10 kilometers. The major contribution in runoff is from Kings River. Lying south of the Kern River delta, there is a depression in the lowest part of which are the beds of Kern and Buena Vista lakes. Waters of Kern River which naturally reach Kern Lake have been diverted and the lake bed is now dry and under cultivation. Buena Vista Lake receives such flood waters from the Kern and smaller streams as are not used for irrigation or absorbed into the underground basins in the Kern River delta. A portion of this lake has been diked off and is used as an irrigation storage reservoir and the remainder is now under cultivation. This cultivated portion, however, is available for the storage of water from major floods. Excess waters which cannot be stored in Buena Vista Lake are diverted toward Tulare Lake through a channel following the trough of the upper San Joaquin Valley. Lying adjacent to this channel, there is one reclamation district, with an area of about 34,800 hectares, which is partially protected by dikes.

In the section of the valley lying along the San Joaquin River upstream from the mouth of the Merced River, the flood plain is wide. The total gross area including river and slough channels, is about 124,000 hectares. Across this flood plain run the winding courses of several sloughs, some of which are as large as the main river channel and in their natural condition carried a large portion of the flood flow. For the most part, such protection as exists in this portion of the valley is afforded by irrigation canal banks constructed along the high ground near the river banks. These works provide protection of varying degrees from overflow by the smaller summer and winter floods for about 50,000 hectares of land.

The group of overflow lands lying along the San Joaquin River from the mouth of the Merced River to the head of the delta at Paradise Dam have a length of about 55 kilometers and is so narrow that the gross area is only about 33,000 hectares. It is generally conceded that complete or even a high degree of protection against unregulated winter floods through this portion of the valley is not economically feasible because a flood channel of

sufficient width to accomplish such protection would utilize a large percentage of the best agricultural lands and the burden of cost would be larger than the value of the protection. A fair degree of summer and small winter floods is feasible, however, and about 13,000 hectares have been wholly or partially protected from such floods.

The City of Stockton has constructed the Valley Springs Reservoirs on Calaveras River, with a capacity of 93.747 million cubic meters for the purpose of controlling floods on the Calaveras River to afford protection of Stockton and adjacent areas. Plans are proposed for raising the dam to increase the reservoir capacity to 203.531 million cubic meters to obtain greater flood protection than afforded by the present structure.

Great Basin section:—At irregular intervals during the early summer, following winters of heavy snowfall the streams of the Great Basin overflow their banks and spread over the adjacent farm lands. The area flooded by local streams is small and the damage minor. No regulatory works have been constructed to control floods, but reservoirs constructed for irrigation and power use materially reduce the peak flows on certain streams.

Imperial Valley, part of which is below sea level, has been subject to severe damage by high floods on the Colorado River, the only protection therefrom consisting of a system of dikes and bypass channels. The completed Boulder Dam and the Lake Mead Reservoir will remove the main Colorado flood hazard.

VI. Conservation by Storage.

Conservation, according to the dictionary, is the preservation of natural resources, for economical use, or from loss or injury. In the case of water supplies the term carries an exactly opposite meaning than it does when applied to most natural resources. To conserve a country's supplies of coal, for example, means curtailment in the use of coal; to conserve water resources means the development and use of them. If water in the arid West is a natural resource, then its preservation for public water supply, for irrigation and for power production must be a conservation function. Nothing is more obvious than that water is a natural resource in India, Algeria and in the western United States. Indeed, it is the primary, the controlling resource, the one which gives value to all other resources, the one without which those regions would be entirely useless.

The humid, semi-arid, or arid region would be equally useless without water, but we generally refuse to take seriously the idea that a humid region could be deprived of water. Such an area might have more or less water, but we do not accept the suggestion, except in theory, that it might become a desert. Here the mind, therefore, fails to recognize water as a natural resource when water is plentiful and is not concerned with its conservation.

The water constantly flowing in the streams and rivers represent a continuous waste of wealth unless they are made to supply power, irrigate lands, or serve other useful purposes. It is not exaggerating the case to say that much of future economic progress will depend upon the development

and use to the fullest extent of these vast potential sources of wealth. In western United States this fact is appreciated more fully, where the continued growth of cities and the development of agricultural and industrial regions in desert country are made possible only through water conservation, but the truth holds to a great extent for the country as a whole or for almost any other region.

Recent technical advances in the arts relating to water conservation have made it possible in many cases to effect low cost of conservation development. These technical advances will have a favorable effect upon future industrial structure as they will make financially feasible many projects, the development of which has heretofore been considered uneconomical.

The results and benefits attained in the past through water conservation indicate to a degree what may be accomplished in the future. Lowering cost of projects, through the use of technical improvements, will be a factor in increasing the importance of water conservation to changing industrial structures for which the keys for future development lies in the advantages that may be obtained from this conservation of water resources.

In most cases of highly developed streams, the natural flow during a large part of the year is deficient for the flow demand, and regulation by storage is desirable. If it is not feasible to obtain reservoirs of sufficient capacity to effect complete regulation, partial regulation is often found advantageous. It is a well known fact that all principal streams are subject to periodical freshets and depletion of more or less severity, and that at regular intervals of five, ten or fifteen years, unusual or extreme floods occur. Such floods carry into the valleys great quantities of dirt, silt, and debris, depositing them over the flat lands, or in the streets, highways of settled communities, and destroying transportation facilities such as railroads and bridges. A menace to health and lives of the people as well as causing damage to property and losses to agriculture and manufacturing industry such floods are happening over wide parts of the Western United States and in southern California in particular.

Through the creation and rational operation of storage reservoirs, and through this means only, will the true conservation of water be accomplished. The floods, which otherwise would run to waste, and causing damage loss while doing so, or pass unused for power, irrigation or industrial purposes, would be restricted and impounded, to be gradually released during the months of the year in which every cubic meter of water can be put to use for municipal water supplies, for the generation of power, for irrigation, the improvement of the sanitary conditions of polluted streams, or the assistance of river navigation, and salinity control in tidal areas.

The extent to which streams can be economically regulated is affected by many practical considerations and depends upon the relation between the value of the benefit from storage and the annual operation, interest and other overhead costs of the reservoirs and dams. The benefit derived from storage is measured by the resulting decrease in energy required from standby facilities to maintain continuous output and by the reduction in peak demand of standby facilities, or, in the case of an independent hydro-

electric plant by the resulting increase in both the energy output and the value of such output, or by the extent to which the hydroelectric energy is made continuous and reliable. Similar considerations as given above in the case of a storage for the production of hydroelectric power, govern in the development of storage for irrigation or for public water supply.

Streams differ greatly in their steadiness of flow during the year. Some which are fed from perennial springs or from large lakes, or from artificial reservoirs of large capacity in which the surplus waters can be stored and released when the stream would otherwise be very low, are very uniform in their flow, varying but little from month to month throughout the year. Other streams, especially those without lakes or large swamps and marshes in their watersheds, and draining steep or rocky districts are extremely varying in their flow and are called "flashy streams". The steadiness of a stream is indicated by the ratio of the ordinary yearly maximum flood to the minimum in the dry season. The nearer the ratio is to the unity the more steady the flow.

The variability of the flow of a stream at any given point is dependent upon various physical conditions, namely; (a) The size of the drainage area above the point considered; (b) the slope of this area; (c) its geological character; (d) its topographical character; (e) the surface conditions, such as extent of forested area within the drainage basin, the area of swamp or marsh land, the area under cultivation, etc. (f) The extent and location of lakes or artificial reservoirs, and their manner of control; (g) the meteorological conditions affecting the drainage area.

The bearing of some of these elements upon the stream flow have been discussed in Part I, and only the geographical and geological elements will be here considered briefly.

Generally speaking, other things being equal, the larger the drainage area the more regular the flow will be. A large stream is as a rule, fed by many tributaries. While all will in general be lowest during the same season of the year, local rains or other conditions will also vary throughout a large drainage area. When one tributary, therefore, is at its lowest, the others will very likely not be at their very lowest, and there will, therefore, be a more steady flow than in the case of a small stream.

The shape of the drainage area and the arrangement of tributary streams have some effect upon the regularity of flow, although they have a greater effect upon the magnitude of a flood at any point on the stream. These elements are intimately connected with other elements of flow and cannot be formulated in general rules. The effect of shape of watershed is of lesser importance but it has some bearing (Swain, 1913).

The geological character of the watershed area improves the regularity of flow when it favors the absorption of the precipitation into the ground and its storage there as groundwater, flowing on flat gradient through the rocks and soils and coming to the surface in the form of springs which feed the streams with a measure of constancy. On the other hand, if the geological conditions of the district favors a rapid runoff of the precipitation from the surface into the superficial river channels, irregularity of flow will

be promoted. A rocky country with a thin soil, especially if composed of impervious non-absorptive rocks, with steep slopes, will afford a rapid runoff of surface waters and will render the streams very variable, especially if the precipitation is likely to come in sudden heavy storms. A deep porous soil, especially if forested or cultivated will facilitate absorption of the precipitation and the regularity of the streams.

In California many streams of the southern Sierra Nevada have granitic watersheds with tendencies to rapid runoff but fortunately here the higher region of tundra type or with heavy snow cover tend to equalize the flow in spite of the rapid runoff from the lower part of the watershed areas. On the lava-covered Plateau of north-eastern California, the precipitation sinks into the porous lava formation and the flow of the rivers is tending toward uniformity. Southern California also presents the porous, absorptive soils of the younger geological formations and the precipitation sinks into the ground except when storms of suddenness and cloudburst character makes the flow large for a very brief period of time, not permitting the runoff to penetrate below the bottom of the Wadi-type surface channels

Where the topography of the country is broken and mountainous, with steep, rocky slopes, especially if accompanied by a thin soil and the absence of forests, the stream draining such an area will generally be very variable. The precipitation will run off almost immediately into the river channels and the streams will alternate between periods of floods, and periods when they are dry. In a flat country, on the other hand, with an absorbent soil the water will not be drained into the streams rapidly but will be absorbed into the ground and will tend to promote steadiness of stream flow.

The capacities of storage reservoirs are often affected by the gradual deposition of silt. In some regions, such as the southern and western United States, these deposits may be enormous and may in a few years, completely fill the reservoir and destroy its usefulness. The conditions in this regard at Lake Mead Reservoir above the Boulder Dam on the Colorado River, and in southern California may serve as illustration:

To provide for a detailed study of silting at Lake Mead, as the basis for possible erosional control on the Colorado River and its tributaries, the Soil Erosion Service, in cooperation with the Bureau of Reclamation and the Coast and Geodetic Survey have mapped in detail 600 square kilometers in the reservoir site. This map to scale 1 : 12,000 shows the original bottom contours and will permit comparative studies to determine change in topography on the lake floor due to deposits of sediment. Contour intervals of the map is 3 meters (10 feet) on steeper, or 1.50 meters (5 feet) on the flatter ground.

Based upon the studies that have been made by the Bureau of Reclamation it is estimated that during the first 50 years of the operation of the reservoir there will be a deposit of about 3,700.56 million cubic meters of silt, which is about 10 per cent of the reservoir capacity of 37,620 million cubic meters. In constructing Boulder Dam, an allowance of 12, 335 million cubic meters was made for silt retention and it would probably take in excess of 150 years for this volume to be deposited and something like 500

years before the reservoir will be entirely filled. In order to prolong the life of the reservoir, plans are being developed for the construction of a series of silt detention dams above Lake Mead, which will extend the life of usefulness of the reservoirs indefinitely.

The mechanical protections will be augmented by erosion control measures designed to combat the problem of sedimentation at its source. Re-vegetation of over-grazed areas and proper range management on the highly erodible lands which drain into the Colorado will reduce soil washing to a minimum and materially reduce the silt load of the river.

Silt measurements in the reservoirs of the Pacific South-west show a generally low rate of silting. This is due in part to the low inflow to the reservoirs and partly to the generally intact vegetation cover over the drainage basin. Where the drainage basin has been burned over, as at Harding Reservoir on an easterly secondary tributary to Santa Ana River, in southern California, the reservoir fills quickly under heavy rain. In this case the reservoir about 800 meters long, was filled with eroded material from the denuded soil within a single month. The Hodges Reservoir, near San Diego has a somewhat higher silting rate than average for California reservoirs, but much less than the general rate in more inland parts of the semi-arid South-west. The Barrett Reservoir and the Morena Reservoir of the San Diego water supply system show low ratios of silt deposit. "In California some high rates of reservoir silting relate for the most part, to watershed fires. Fire prevention, quick re-seeding of burnedover areas and treatment of gullies in earliest incipient stage would appear to be generally in order to keep rates in non-agricultural areas at a minimum. When erosion of cultivated lands is involved, as at Lake Hodges and other reservoirs of the lower foothills, modern erosion control methods are applicable" (Eakin, 1936).

Up to the present time no effective method has been found for removing silt from a reservoir except that which has been deposited nearest the dam, which can be washed out. Life of reservoirs vary greatly, from as low as 21 years (when reservoir has been in use for 12 years), and an annual depletion of storage capacity of 1.91 per cent for the Rogers Reservoir; 32.6 years (when reservoir had been in use for 5 years) and an annual depletion of 2.48 per cent for Lake Waco, both in Texas, to 165 years (when reservoir had been in use for 6.33 years) and an annual depletion of 0.47 per cent for the San Carlos Reservoir on Gila River, Arizona, and 241 years (when reservoir had been in use 8.75 years) and annual depletion of 0.36 per cent for Lake Michie, Durham, North Carolina.

The specific gravity of silt transported by the Colorado River is normally 2.64, the weight per unit varying considerably. The dry weight per cubic meter of Colorado River sediment varies from 635 kilograms for fine silt deposited in settling basins in Imperial Valley to 1,550 kilograms for bed silt in the canals. The estimated normal quantity of silt annually transported to the lower end of the Canyon section is 230 million metric tons, or 169 million cubic meters. The average annual cost of silt removal from irrigation systems of the Imperial Valley amounts to more than one million

dollars (This study of the Bureau of Reclamation presents a 37 per cent higher silt carrying value of the Colorado River than earlier stated in Technical Bulletin No. 67 of the Department of Agriculture).

The development of water resources for the use of man is one of the oldest arts known, and its history is exceedingly fascinating. The primitives appreciating the needs of water storage, enlarged or improved the water holes, or made cisterns. Among the oldest monuments of technical skill are the works connected with water supply. Through all historic time there has been some progress but since the beginning of the twentieth century the number and magnitude of works undertaken is astonishing.

At a very early period of history the construction of earthen dams called "Tanks", to impound waters was in practice by the natives of India, and in some places, notably in central and southern India, in the Deccan, Madras and Mysore, there are immense numbers of them. In Madras Presidency, including Mysore, there are said to be about 75,000 tanks and in 1866 Major Sankey reported that the percentage of the whole area of Mysore under tank system was 59.7 while the total area of the state is 70,700 square kilometers, one-third of the tanks were for irrigation. In the Madras Presidency, without Mysore, were in 1882, 53,000 tanks having about 48,000 kilometers of embankments, and 300,000 structures, weirs, escapes, etc. In modern times the British engineers have constructed a number of very large tanks, the higher of which have masonry core walls. The conditions controlling the location of a tank are similar to those for reservoirs. The water supply must be adequate to fill the tank, the location must be such that a suitable dam can be constructed at a reasonable cost and ample spillway must be provided.

These old dams or tanks, have withstood successfully the ravages of time in a remarkable manner. One of them the Virainum Tank, formed by an earth dam almost 20 kilometers long, and the reservoir covers 90 square kilometers, is still in use (Wegmann, 1927); the Ponriary Tank of Trichinopoly, which is no longer in use had a water surface of 155 to 210 square kilometers, had a dam of a length stated variously to be from 20 to 48 kilometers; the Chembrambaukam Tank, having an embankment 5.0 to 8.50 meters high and 5.85 kilometers long and covering 2,320 hectares; and the Chauverypauk Tank, which has been in use for from 400 to 500 years, is 6.0 kilometers long, revetted on the water side by a stone wall 6.70 meters high, 1.80 meters thick at the bottom and 0.90 meters at the top. This wall rises to a level 0.90 to 1.20 meters above high water in the reservoir, the crest of the embankment, which is 3.60 meters wide, rises 2.70 meters above high water. The upstream and downstream slopes are respectively $2\frac{1}{2}:1$, and $1\frac{1}{2}:1$. The exposed surface of the embankment is carefully turfed and planted with grass.

In Ceylon there are 30 very large tanks, besides several hundred in ruins. The great tanks of Ceylon exceed the Indian tanks in extent, the tank of Kalaweva, constructed A.D. 459, had a circumference of 65 kilometers. It was formed by an embankment 20 kilometers long, which had a spillway of stone. The tank of Padavil in Ceylon had an embankment 17.50 kilome-

ters long, 9 meters wide at the top and 61 meters at the base, and about 21.50 meters maximum height. The sluiceway structure carried a great deal of cutstone ornamental work. The Madduck tank built over 400 years ago (Wilson, 1892), and now abandoned, had a capacity of about 1,000 million cubic meters. The principal of the three dams of the reservoirs had a height of 28 to 33 meters and a base width of 290 to 335 meters. It failed for lack of spillway. The Giant's Tank has an embankment over 90 meters thick at the base which can be traced for more than 28 kilometers, and was intended to cover 580 square kilometers but was never used owing to an error in the levels which would have obliged the water in the canal that was to supply the tank to run uphill (Wegmann, 1927).

Modern earth dams in India have been built in large numbers and will not be taken up here. Some of the older ones is the Ekrak Tank near Sholapur, and the Ashti Tank, on the Ashti River. The former has a maximum height of 22 meters and a total length of 2.20 kilometers, including the masonry sections at the north and south and of 430 and 400 meters length respectively. The Ashti dam has a maximum height of 17.70 meters and a total length of 3.80 kilometers. The crest of the dam which is 1.80 meters wide is placed 3.60 meters above high water. The inner slope is paved with stone, the reservoir covers 1,085 hectares and stores about 40.351 million cubic meters. About 28 per cent of this storage is lost annually by evaporation (Wilson, 1892).

In comparatively recent times began the construction of masonry dams. This method of construction seems to have been first adopted in southern Spain, where, about the sixteenth century large reservoirs for irrigation were constructed. Many of these early spanish dams were of great dimensions and their proportions demonstrate that their designers and builders had no knowledge of the forces to be resisted and (Wegmann, 1927) claims that some of the dams would have been stronger had their upstream and downstream been reversed. The French engineers were the first to evolve a theory of the stability of dams (Sazilly, 1853).

The oldest existing masonry dam is that of Almanza, situated in the province of Albacete, near the town after which it is named. The exact date of completion is unknown, but it appears from old documents to have been in use before 1586. It was founded on rock, built of rubble masonry, faced with cut stone except the upper 6 meters of the upstream face which was built of rough ashlar with courses of cut stone at intervals. The lower part of the dam to a height of 14.60 meters is curved in plan, convex upstream, the radius of the back facing being 26.24 meters. The upper part of the dam, probably constructed later has a plan whose center line forms a broken line 89 meters long. The maximum height of the dam is 20.70 meters. Spillway was provided at one side by excavating the rock to 2.0 meters below the crest for a length of 12 meters.

Water is drawn for irrigation through a gallery 1.0 meters square passing through the lower portion of the dam. Above the downstream of this outlet channel a chamber is constructed through the dam serving for scouring out of sediment, has a dimension 1.30 meters wide by 1.50 meters high.

Wegmann points out that although this dam is not well proportioned it is an interesting fact that its masonry has sustained safely for three centuries a greater unit stress than in any other masonry wall, namely 14 kilograms per square centimeter.

The Alicante Dam is the highest of the old Spanish dams, named also after a village near its site, the dam of Tibi. It was constructed during the years 1579-1594, to supply the arid region of Alicante with water for irrigation. The calcareous rocks of the gorge or Tibi stand almost vertical, the bottom width is only 9 meters and at the top of the dam 58 meters. The length of the reservoir, which is on the Monegre River is 1,800 meters and has a capacity of 3.7 million cubic meters. The dam is built of masonry faced with large cut stones. Its maximum height is 41.0 meters, and is curvilinear in plan on a radius of 107.13 meters. Maximum unit stress in the masonry is 11.3 kilograms per square centimeter. Numerous other old Spanish dams have been recorded and described in the extensive literature on masonry dams.

The French engineers built a number of dams before the publication of M. de Sazilly in 1853, and in general those have lighter profiles than the old Spanish dams, but show, nevertheless an absence of a rational theory of design. The oldest French dam described is the Lamy built in the years from 1776 to 1782, with a height of 15.65 meters. With the Furens Dam (French) built from 1858 to 1866, the Gileppe Dam (Belgian) 1870 to 1875, the Vyrnvy Dam (English) 1882 to 1890, the Remscheid (German) 1889 to 1892, the modern era of masonry dam construction dawned. Advancement in technical science and methods of construction of dams has been rapid in all countries of the civilized world. In America, for instance, there is a wide step in advance from the Boyds Corner, Bridgeport, San Mateo, Bear Valley dam structures to the latest creations, the Norris, Boulder, Grand Coulee, Owyhee, El Capitan, San Gabriel dams.

Modern types of dams are of various fundamentally different design the principal ones of which are as follows:

Gravity Dam, is one in which the pressure of the water is resisted by the weight or gravity of the dam itself. This type of dam may be either straight or curved, but is always solid. By arching or curving the dam in plan there is a lateral transfer of load to the canyon wall.

Single-arch Dam, can be used where the canyon span is relatively narrow and the canyon walls consist of sound rock capable of taking arch thrust. It requires less concrete or masonry and can consequently be constructed at a lower cost than the gravity type.

Multiple-arch Dam, is one consisting of a series of arches supported by intermediate buttresses. This type requires considerable less concrete than a gravity dam.

Earthfill Dam or Rockfill Dam, are built where the foundation consists of earth, sand or other pervious unstable material. The earthfill is deposited by layers and compacted by rolling, or sluiced into place by water, designated, respectively as "rolled fill" and "hydraulic fill".

Hydraulic fill dam, is one in which the materials are transported and placed in the embankment by means of water.

Semi-hydraulic fill Dam, has the materials transported to the site by other means than water, and segregated, placed, and consolidated by the use of water.

The upstream face of an earthfill dam is protected from wave action by facing the slope with rock or gravel, or concrete paving. Percolation through the structure is prevented by a puddle core or masonry cutoff wall, or both. The usual practice with a rockfill dams is to line the upstream face with concrete and place a cutoff wall at the upstream toe. Overtopping of an earthfill or rockfill dam is prevented by providing ample freeboard and spillway capacity (Taylor, 1932).

The first dam in California was built by the Spanish padres of the Order of San Francisco. When the 21 historic missions of California were founded it was necessary to construct adequate water supply systems in each case, usually consisting of small diversion dams, ditches and conduits of clay pipe. A few of these are still in use.

The first mission, San Diego de Alcalá, was founded in 1769 by Padre Junipero Serra. Some years later, a water supply and irrigation system was built and as a unit in this system the first of all California dams was built here about 1800. It has long been an attraction to tourists because of historical lore, but it is gaining engineering attention from tributes to priestly scientific skill. Engineers have concluded, when going up and down the San Diego River, in search of dam sites that Fra. Junipero Serra and his associate padres built in the right place first. The dam was built across the channel of the river about 16 kilometers from the outlet in Mission Bay, and its location was determined by a convenient outcrop of rock which reduced the amount of excavation, for stable foundation material.

Structurally, this old mission dam, which, after more than 130 years lets flood waters rush over it as intended, may be termed a masonry dam though the core is of adobe. The dam was 68.50 meters long, 4.28 meters high and 3.56 meters thick at the base, and was apparently built of large baked bricks, with the entire structure faced with rubble masonry. "They founded the structure on rock and built well. The mortar was made of hydraulic lime which they themselves burned. History and opinion differ as to the source of this material, some claim that limestone was transported from the mountains, others that a local material was used. Near to the dam site a geological example of the origin of this region, a 6 meters high bank entirely made up of shell formation shows a possible source of some of the material for their lime kilns." (Griffith, 1930.)

The dry channel is at times a real river, justifying its name. Successive floods have deposited sediment on the upstream face level with the top of the dam. The opening for the sluice gate is still in evidence. Water was conveyed by a baked tile aqueduct, portions of which are still to be seen.

Presumably built by Indian neophyte labor, the dam represents a labor of love, although a Spanish sword or lash may have helped a little, for there was a lot of rock and mortar to haul without the aid of motor lorries.

Among the earliest high earth dams in California were the Pilarcitos, San Andres, and the Upper Crystal Springs Dams for the Spring Valley Water Company, then furnishing water to the city of San Francisco. The first of these, the Pilarcitos, on Pilarcitos Creek, San Mateo County, California, was built in 1868-1869. Its effective height according to present day ideas is but moderate, about 27.50 meters. Its notable feature was a puddle trench 9 meters deep. The San Andres also had a puddle trench 13.70 meters deep and the Upper Crystal Springs Dam where the depth of puddle trench was 29.90 meters. The Upper Crystal Springs Dam suffered no injury in the 1906 earthquake except for the spillway tunnel which was sheared off completely and the two parts were connected with an S-bend at the offset of about 2.40 meters.

A number of early dams in California were built of logs, especially in the mountainous regions. The old Strawberry Creek Dams were of this type. Located on Strawberry Creek a tributary of the South Fork of Stanislaus River the dams were built in 1856. Logs of the tamarack pine variety with butt diameters up to 1.20 meters were used in their construction, and they carried a heavy plank deck the lower end of which was made watertight with the river bottom. Their effective height was about 12 meters and overflow over the crest served as spillway, their watershed was small, of the High Sierra granite type, from which very little silting took place.

The La Grange Dam on the Tuolumne River near the point where the river breaks out of its mountain canyon. The dam is of gravity type built of rubble concrete and rises about 36 meters above the original surface of the river bed. It is arched upstream to a radius of 91.50 meters and has a crest length of 94.50 meters. It is an overfall structure. The dam was completed and reservoir filled to overflow about Christmas 1892 (Grunsky, 1931).

The Old Lower Otay Dam, near San Diego, California failed in 1916. It was a freak type of dam built in 1893-94, which served as long as it did only because very wet winters are not of frequent occurrence in southern California. When it failed about 30 lives were lost. It consisted of a steel diaphragm set on a concrete base and both sides of the steel plates were protected from rusting by a concrete cover. This diaphragm was supported by a rockfill on the downstream side and an earthfill on the upstream side, both on slopes 1 vertical:1¹/₂ horizontal. The diaphragm did not reach the top of the dam but stopped 0.90 meter below. The spillway was insufficient. There had been no high water of consequence for many years, none from 1894 to 1916. A professional "Rainmaker" Hadfield, was employed by the City of San Diego to make it rain. His success exceeded expectations, but neither he nor anyone else could stop the rain once it had commenced and the disaster followed. The Lower Otay Dam collapsed, and other dams were menaced because of insufficient spillway capacity. The New Lower Otay Dam is a modern concrete structure.

There are a great number of these early dams of various types in California of which only a few might be mentioned in addition to the above;

Blue Lakes Dam, rockfill; Wilde Horse Dam, earthfill; Purisima Dam, concrete arch; Merced Falls Dam, timber frame and deck; Bear Valley Dam, exceedingly thin arch 19.50 meters high.

The number of dams in California today is probably over 1000. The Division of Dams of the State Department of Public Works charged with the supervision of dams has recently completed a seven year study of 950 dams in the state where all dams of over 3 meters (10 feet) height or having a storage capacity of more than 12,335 cubic meters (10 acre feet) were under state jurisdiction according to the Dam Act of 1929. This Act has later been revised to include dams from 7.63 meters (25 feet) or 61,676 cubic meters capacity (50 acre feet). In a recent article (Hawley, 1936), the following list as to number and present status of dams in California is given.

Dams under State Supervision classified as to types:

Type ¹	Number	Per cent of total
Embankment Type		
Earthfill, compacted, hydraulic or semi-hydraulic	379	64.5 ¹
Rockfill	39	6.6
Concrete or Masonry type		
Gravity	50	8.5
Arch; variable radius	25	4.3
constant radius	34	5.8
Buttress; multiple arch	15	2.5
slab	19	3.2
Timber and miscellaneous	27	4.6
Total	588	

In the article referred to the author emphasizes that "Spillways of inadequate size, too much left to chance in materials and construction methods, lack of proper emphasis on geological studies of foundations—these are typical of the most common faults in the 950 California dams examined in recent years by state authorities".

The Dam Act of 1929, which was passed after the catastrophic failure of the St. Francis Dam of the Los Angeles Water Supply System on March 12-13, 1928, provides for (1) inspection of existing dams; (2) approval of plans and specifications and for inspection of construction of new dams or the enlargement, alteration, repair or removal of existing dams; (3) supervision over maintenance and operation of all dams in so far as necessary to safeguard life and property.

The total number of dams built prior to the effective date of the Act (Aug. 14, 1929) which were examined critically by the department is 830. During the period from Aug. 14, 1929, to January 1, 1936, the department reviewed plans, specifications and sites and supervised as to safety the

¹ These percentages differ very little from those applying to a classification of all dams examined.

construction of 110 dams, which cost 60 million dollars and added to the state's water storage 1,233.52 million cubic meters. Enlargements of existing dams numbered 30 at a cost of 4.60 million dollars making available approximately 206.70 million cubic meters of increase storage.

Dams now under state jurisdiction total 588, representing a storage capacity of 8,634.64 million cubic meters and a total capital investment of 200 million dollars. The total storage capacity of all California reservoirs created by constructed dams including those not under state supervision probably approaches 15,000 million cubic meters or 15 cubic kilometers. This volume is about 40 per cent the volume of the Lake Mead Reservoir back of the Boulder Dam structure on the Colorado River.

The dams in California include numerous types, a wide variety of purposes, elevations from sea level to 3,350 meters above. Some are in arid areas while others are in basins subject to rainfall of cloudburst intensity (for example, since the study began a 116.5 square kilometer watershed in which rainfall usually is very low experienced a runoff of 5.46 cubic meters per square kilometer per second), or to heavy snow. The dams vary widely in height; many are outstanding structures of their respective types. Some are constructed at sites where the geology is of major importance, as across earthquake faults (Hawley, 1936).

Conservation by storage for the production of power, on most streams, is, where possible, a very important factor. Its value lies, not so much in the value of the kilowatt hours generated during the low flow season, by the use of the water actually stored, as in the lower installed capacity made possible and the consequent increase in kilowatt hours obtainable from natural flow during a large portion of the year. Most power demand is for "prime power", available at any time in all seasons. "Secondary power", that available only during certain hours or season, is in much less demand at much lower rates.

The ideal location for storage is near the headwaters, so the stored water may be utilized through as much as possible of the head in succeeding plants. The best examples of California power water storages are Lake Almanor on Feather River, Florence Lake and Huntington Lake on the San Joaquin River, Spaulding Lake and Lake Fordyce on Yuba River, Silver Lake, Twin Lakes, Echo and Medley Lakes on the South Fork of American River etc. Such sites are not always available, but will bear greater cost per unit of storage than those not so located. Afterbay regulation in some cases takes care of the different demand in flow of water for power which is often variable during the day, and irrigation which makes a more constant demand on water during the irrigation season. This afterbay regulation is provided between the power house tailrace and the intake to the irrigation canal to absorb fluctuations due to load factor.

Most watersheds in California, contributing runoff susceptible of use in power development, are rocky and precipitous, provide little ground storage and have a rapid runoff from rain or melting snow. In California the winter season constitutes the most valuable storage. The conservation of snow is dependent on mountains and forests and is most complete where

Short List of Large Dams and Reservoirs in California.

Name and location	Elev. above Sea Level Meters	Type	Year Com- pleted	Height in Meters above		Crest Length Meters	Storage Capacity in Thousand Cubic Meters	Drainage Area Square Kilometers	Contents of Dam in Thou- sand Cubic Meters	Approx- imate Cost in Dollars
				Stream- bed	Founda- tion					
E m b a n k m e n t										
El Capitan, San Diego River	234.8	Semi-HF ¹	1936?	66.18	82.35	354.0	145,555	492.1	2,130.0	3,226,600
Calaveras, Calaveras Creek	236.4	HF ²	1925	62.52	67.10	366.0	123,352	259.0	2,650.0	3,888,125
Upper San Leandro, S. Leandro Cr.	144.9	HF	1926	57.90	67.10	201.5	51,111	80.3	955.0	—
Arrowhead, Little Bear Creek	1,559.8	Semi-HF	1922	54.90	61.00	220.0	57,975	17.8	1,146.0	500,000
San Pablo, San Pablo Creek	100.0	HF	1920	51.20	62.50	381.0	53,279	90.6	1,682.1	—
Priest, Rattlesnake Creek	684.7	HF	1923	51.20	—	354.0	2,899	2.7	562.0	1,000,000
Crane Valley, N. Fk. S. Joaquin R.	1,030.9	HF + RF ³	1910	44.20	—	373.0	55,500	142.5	695.0	1,450,000
Lower San Fernando, S. Fernando Cr.	348.3	HF	1920	43.30	—	736.0	23,300	36.8	2,161.0	1,466,000
Almanor, N. Fk. Feather River	1,377.1	HF	1927	41.20	—	381.0	1,613,444	1,303.0	1,170.0	2,632,000
Henshaw, San Luis Rey River	835.7	HF	1928	37.50	47.60	395.0	251,120	531.0	382.3	2,000,000
Cajalco	418.1	RE ⁴	1935	59.20	61.00	123,352	103.6	2,755.0	—	—
Bouquet Canyon, Bouquet Creek	917.4	RE	1934	57.95	68.60	583.0	44,653	35.2	2,615.0	3,007,586
Stone Canyon, Stone Canyon Creek	259.2	RE	1924	49.40	67.10	173.0	9,819	3.5	557.5	613,727
Puddingstone, Walnut Creek	299.5	RE	1928	44.84	54.90	822.0	21,461	33.3	661.0	729,908
Santiago, Santiago Creek	247.0	RE	1931	41.48	47.58	427.0	30,838	162.5	604.0	900,000
Lower San Leandro, S. Leandro Cr.	74.1	RE	1892	41.18	—	137.3	17,023	111.5	476.0	—
Coyote	243.4	RE	1934	38.73	50.33	37,006	37,006	300.0	865.0	—
San Gabriel No. 1, San Gabriel R.	451.7	RF + E ⁵	1937	97.60	112.85	442.5	69,077	531.0	7,844.8	16,860,000
Salt Springs, N. Fk. Mokelumne R.	1,207.2	RF	1931	95.46	105.22	396.5	160,358	478.0	2,293.8	6,930,000
San Gabriel No. 2, W. Fk. S. Gabriel R.	733.5	RF	1937?	80.82	88.45	183.0	16,036	106.5	917.5	2,700,000
Bowman, Canyon Creek	1,697.9	RF	1927	52.15	53.37	213.5	77,712	74.9	229.4	680,000
Morena, Cottonwood Creek	929.9	RF	1895	50.93	85.09	167.8	81,166	310.0	256.0	1,250,000
Main Strawberry, So. Fk. Stanislaus R.	1,714.1	RF	1916	43.92	51.85	186.6	22,203	70.7	252.5	985,000
Fordyce, Fordyce	1,976.4	RF	1926	42.70	—	323.5	57,729	78.1	318.5	1,870,000
Relief, Relief Creek	2,338.7	RF	1910	42.40	44.22	154.0	18,651	72.0	104.75	850,402
Bucks Creek, Bucks Creek	1,576.2	RF	1928	37.21	39.04	372.0	127,053	72.5	268.0	2,359,492

	1935 ²	74.72	99.12	229.0	48,477	543.0	344.07	5,770,000
Morris, San Gabriel River	358.4	Str. in pl.						
Mulholland, Weid Canyon	228.7	Cur. in pl.	59.47	61.00	284.5	5.23 ⁵	2.6	132.5
Shaver, Stevenson Creek	1,637.8	Str. in pl.	1927	55.81	661.5	166,874	78.6	215.62
Huntington, Big Creek	2,119.7	Cur. in pl.	1917	48.19	50.32	400.0	204.0	89.4
Barrett, Cottonwood Creek	493.2	Cur. in pl.	1922	44.30	58.50	229.0		
Savage, Otay River	150.1	Cur. in pl.	1919 ²	44.22	50.03	213.5	255.5	106.7
Lower Crystal Springs, San Mateo Cr.	87.8	Cur. in pl.	1888	42.70	49.97	183.0	66.61 ⁶	120.1
Scott, So. Eel River	585.6	Str. in pl.	1921	41.17	42.79	248.5	117,015	603.0
Hemet So. Fk. S. Jacinto River	1,322.5	Cur. in pl. M. ⁸	1895	41.17	45.14	214.0	173.5	24.7
Copco No. 1, Klamath River	797.0	Cur. in pl.	1922	40.26	75.33	126.5	11,173.0	53.75
La Grange, Tuolumne River	89.7	Cur. in pl. M.	1894	39.95	94.5	3.701	4,000.0	30.38
Pit No. 3, Pit River	850.4	Cur. in pl.	1925	39.65	151.0	39,720	12,295.0	62.1
Pacoma, Pacoma Creek	614.0	vari. rad. ⁹	1929	108.27	113.76	174.0	7.778	172.9
Spaulding, So. Yuba River	1,529.3	vari. rad.	1919	83.87		244.0	91,822	146.5
Big Santa Anita, Big Santa Anita Cr.	404.1	vari. rad.	1927	68.62	71.67	184.5	1,699	58.3
Big Tujuanga, Big Tujuanga	702.7	vari. rad.	1931	62.22	74.42	125.0	7,710	82.7
Bullards Bar, N. Yuba River	497.8	vari. rad.	1924	58.25	60.08	158.7	38,842	1,255.0
Melones, Stanislaus River	220.5	const. rad. ¹⁰	1926	50.63	57.03	180.0	138,771	2,331.0
Saw Pit, Saw Pit Creek	419.4	const. rad.	1927	45.75	49.41	159.0	587	8.5
Gibraltar, Santa Ynez River	416.3	const. rad.	1920	45.75	54.90	300.0	16,956	507.5
Juncal, Santa Ynez River	680.1	vari. rad.	1930	43.31	48.80	131.3	8,714	36.0
Big Creek No. 6, San Joaquin River	680.1	const. rad.	1923	39.65	41.17	151.0	1,225	3,100.0
Hogan, Calaveras River	199.5	vari. rad.	1930	38.12	39.65	417.5	93,748	940.0

B u f f e r s

	1929	43.00	51.85	149.5	1,591	11.14	34.5	911,000
Big Dalton, Big Dalton Creek	521.8	multi. arch ¹¹						
Florence Lake, S. Fk. San Joaquin R.	2,235.3	multi. arch	1926	42.70	46.66	948.0	441.0	43.25
Hodges, San Diego Creek	100.6	multi. arch	1918	39.65		222.5	784.0	13.85
Little Rock, Little Rock Creek	994.3	multi. arch	1891	38.12	48.19	229.0	171.0	24.55
Murray, Trib. Chapparel Creek	104.7	multi. arch	1919	30.80	34.16	263.5	9.7	6.28
Bear Valley, Bear Creek	2,057.5	multi. arch	1911	27.45		110.7	7,295	98.5
Tiger Creek, Tiger Creek	1,093.7	Slab a. buttr. ¹²	1931	30.50	31.41	143.5	646	3.58
Pit No. 4, Pit River	749.7	Slab a. buttr.	1927	21.35	30.60	126.6	23.3	10.32
							12,295.0	32.6

¹ Semi-Hydraulic fill. ² Hydraulic fill and Rockfill.

in plan. ⁷ Straight in plan.

³ Hydraulic fill and Rockfill.

⁴ Rolled earth.

⁵ Rockfill-impervious earth section.

⁶ Curved

¹⁰ Constant radius.

¹¹ Multiple arch.

¹² Slab and Buttriss.

these two factors are combined. The mountain range is not only the recipient of more snow than the plain or the valley at its base but in consequence of the lower temperature prevailing on its slopes the snow there melts more slowly. However, mountains, because of their elevation, are exposed to the sweep of violent winds which not only blow the snow in considerable quantities to lower levels, where the temperature is higher, but also dissipate and evaporate the snow to a wasteful degree. The southern slopes, also, are so tilted as to be more completely exposed to the direct rays of the sun, and in the Sierra Nevada are subjected to the persistent action of the prevailing south-west wind.

On the other hand, the mountain mass, by breaking the force of the wind, catching of the snow and holding it in position even on the windward slopes of the mountains is of importance. On the lower slopes, where the wind is less violent, the forests catch the falling snow directly in proportion to their openness, but conserve it after it has fallen directly in proportion to their density. This phenomenon is due to the crowns of the trees, which catch the falling snow and expose it to rapid evaporation in the open air but likewise shut out the sun and wind from the snow that has succeeded in passing through the forest crowns to the ground. Both mountains and forests, therefore, are to a certain extent wasters of snow; the mountains because they are partially exposed to the sun and wind; the trees because they catch a portion of the falling snow on their branches and expose it to rapid disintegration. However, the mountains by their mass and elevation conserve immeasurable more snow than they waste and forested areas conserve far more than the unforested. If the unforested mountain slopes can be covered with timber, much of the waste of snow occurring on them can be prevented, and by thinning the dense forests the source of waste in them also can be checked.

Another source of natural storage is in the porous structure of the lava-covered plateau of north-eastern California, which contributes the flow to such streams as Pit River and McCloud River, where the flow is quite uniformly maintained during the year except for short storm periods. The Klamath Lake in Oregon, and Honey Lake, Lake Tahoe and others in the Sierra Nevada Mountains also tend toward natural storage regulation.

The development of storage reservoirs in California began, on a small scale during the early days of hydraulic mining. These have increased to many hundreds as just stated, a very large number of which are used for storage and regulation in connection with hydroelectric development. A number of these storage reservoirs are operated solely for the benefit of power production, while many are operated in accordance with irrigation demand, the power production being secondary. The combined storage capacity of these reservoirs is about 7,500,000,000 cubic meters of which approximately 5,003,486,000 cubic meters are available annually, the balance being cyclic storage. This volume of storage represents a constant flow of 160 cubic meters per second for one year. There is a record of more than 150 proposed storage reservoirs in connection with hydroelectric projects. These have a combined capacity of approximately 17,505,334,000

cubic meters which is equivalent to a constant flow of 555 cubic meters per second for one year. A tabulation of available and potential storage follows:

Table 12. Available and potential power storage by sections.

	Available million cubic meters	Potential million cubic meters	Total million cubic meters	Section percent of California	Percent of section developed
North Pacific	579.384	5,631.019	6,201.403	27.5	10.3
San Francisco Bay	—	—	—	—	100.0
Central Pacific	0.604	0.0	0.604	0.0	100.0
South Pacific	88.935	4.194	93.129	0.4	95.5
Sacramento	1,614.985	8,075.865	9,690.850	43.0	16.7
San Joaquin	1,980.875	3,317.772	5,298.647	23.5	37.4
Great Basin	798.703	476.484	1,275.187	5.6	62.5
Total	5,063.486	17,505.334	22,568.820	100.0	

Table 13. Storage capacity for municipal purposes and irrigation.

Section	Capacity of Constructed Surface Storage Reservoirs			Volume of Utilized Free Water Space in Under-ground Reservoirs	Total Utilized Capacity	Total Net Average Annual Yield
	Irrigation	Municipal Purposes	Total			
	Million Cubic Meters			Million Cubic Meters		
North Pacific . .	1,213.79	6.16	1,219.95	49.34	1,269.29	725.309
S. Francisco Bay	3.70	384.86	388.56	863.46	1,252.02	317.015
Import from San Joaquin .						¹ 46.874
C. Pacific . . .	14.70	19.74	34.54	1,233.52	1,268.06	450.235
S. Pacific	462.57	415.70	878.27	5,304.14	6,293.42	² 1,825.609
Import form Great Basin .		111.02	111.02			¹ 246.704
Sacramento . .	1,004.08	8.64	1,012.72	1,233.52	2,246.24	3,320.636
San Joaquin . .	1,252.02		1,252.02	9,868.16	11,686.37	5,929.530
Export to S. Fransico Bay		566.19	566.19			46.874
Great Basin . .	2,430.03		2,430.03	1,233.52	3,767.17	4,588.695
Export to S. Pacific . . .		103.61	103.61			246.704
Import from Colorado River						2,602.727
Totals	6,380.99	1,615.92	7,996.91	19,785.66	27,782.57	20,053.334

¹ Includes 450.235 million cubic meters contributed to groundwater reservoirs by rainfall on valleys and plains.

² These figures were not used in obtaining totals as they have been already included under "export" in other basins.

The extent to which the water resources of California are conserved by storage, for public water supply and for irrigation has been estimated (Huber, 1935), measured by the volume of storage available and the net average yield of water resulting therefrom. The total volume of available storage aggregates 27,782,570,000 cubic meters of which 19,785,660,000 cubic meters is available in underground storage space, and 7,996,910,000 cubic meters have been provided by the creation of surface reservoirs. The surface storage space aggregating 7,996,910,000 cubic meters may be divided into that devoted to public water supply totaling 1,615,920,000 cubic meters and that devoted to irrigation totaling 6,380,990,000 cubic meters. In the different sections these storage are distributed as follows.

VII. California State Water Plan.

With the completion of all the projects whose works consist for the most part of storage dams for the individual project, or of diversion dams, and distribution canals, necessity has arisen for the organization of large areas in single enterprises that overlap areas already organized in irrigation and reclamation districts. The Water Storage District Act of 1921 and the Water Conservation District Act of 1923 have resulted. Even more than in the past will the future be concerned in the expansion of irrigation to additional areas in California and the perfection of the supply of those lands now watered. It is therefore essential that the state activities should be guided by thoughts for the orderly and economical development of its water resources, so that all the needs of civilization for water may be supplied while the predominant use for agriculture may expand to the full limit of its wealth-producing powers (Haley, 1928).

The Central Valley Project, a part of the California state water plan is the result of more than 15 years of exhaustive investigations and is an initial unit in the comprehensive plan evolved for the orderly development of water resources and practicable solution of the water problems of California. This water problem lies primarily in unequal geographical distribution of water resources as related to the needs of a semi-arid state. The comprehensive statewide plan combines the most effective progressive development of streams for navigation and regulation and the utilization of available waters for the production of power, flood control, irrigation, domestic supply, and other uses.

As outlined in the Bulletins of the Divisions of Water Resources of the California State Department of Public Works the Central Valley Project includes the following items of construction (Bull. 12, 13, 25, 26).

(1) Kennett dam and reservoir	\$60,601,900
(2) Kennett power plant	14,251,900
(3) Keswick afterbay dam and reservoir	2,024,600
(4) Keswick power plant	4,862,200
(5) Kennett power transmission line and substation	13,621,800
(6) Sacramento-San Joaquin delta cross-channel	3,867,300
(7) Contra Costa conduit	2,417,300

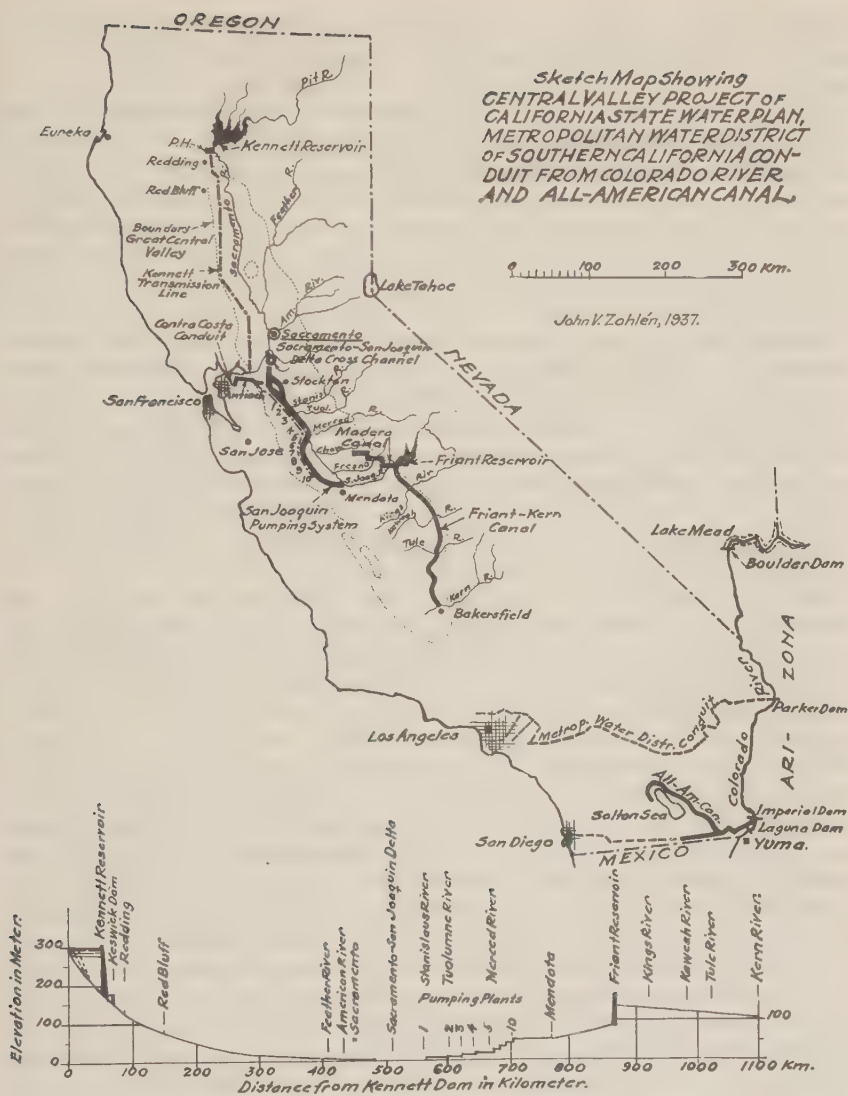


Fig. 11.

(8) Friant dam and reservoir	13,646,800
(9) Friant power plant	1,456,300
(10) Madera Canal	3,211,700
(11) Friant-Kern Canal	25,723,400
(12) San Joaquin pumping system	14,269,300

Total \$159,954,000

Construction costs shown are based on a federal grant for 30 per cent of the labor and materials and interest at 4 per cent on the remainder of the cost.

Kennett dam will be a gravity concrete structure on Sacramento River in Shasta County 21 kilometers above Redding and will have a height of 128 meters above lower water, crest length of 740 meters, and a base thickness of 96.20 meters. A freeboard of 1.53 meters is provided, the reservoir having a storage capacity of 3,626,549,000 cubic meters. Net spillway length will be 122 meters and depth of spillway gates 6.10 meters. There will be 21 flood control outlets 4.28 meters square and seven irrigation outlets 3.31 meters in diameter.

Kennett reservoir necessitates relocating the Southern Pacific Railroad, this work involving 52.50 kilometers of new line with 3,800,000 cubic meters of open excavation, 9.25 kilometers of tunnels, 900 meters of steel viaducts and bridges, and a total of 65.30 kilometers of track including passing track. State highway relocation will require 14.50 kilometers of grading and paving and three major bridges. Dam and spillway construction calls for 1,365,000 cubic meters of excavation and 2,480,000 cubic meters of concrete, other main items being 1,200 tons of steel drum gates and 9,300 hectares of reservoir cleaning.

Kennett power plant, located just below the dam, will contain eight generating units each consisting of a 42,000 horse power turbine and 27,500 kilowatt generator, total installed capacity 275,000 kilovolt-ampere. The two main penstock tunnels will be 7.93 meters in diameter with 6.10 meters diameter steel penstocks.

Keswick afterbay, extending from Kennett dam 14 kilometers downstream, will have a capacity of 17,270,000 cubic meters and will be formed by a gravity concrete dam 29 meters high by 525 meters length. Spillway net length will be 106.75 meters, with 9.15 meters depth of gates. Eight 2.44 by 4.57 meters outlets will be installed. Keswick power plant 180 meters below the dam, will contain four 15,000 horse power turbines connected to 10,000 kilowatt generators. Diameter of the two main penstock tunnels will be 6.40 meters. Major items in these units of construction include: Kennett power plant—62,900 cubic meters open excavation, 67,100 cubic meters of tunnel excavation, 50,200 cubic meters of concrete, 525 tons structural steel, 10,600 tons steel pipe. Keswick afterbay—151,500 cubic meters excavation, 53,400 cubic meters of concrete, 1,750 tons steel drum gates. Keswick power plant—58,300 cubic meters open excavation, 26,800 cubic meters tunnel excavation, 20,500 cubic meters concrete, 255 tons structural steel, 107 tons steel trash racks, 485 tons steel pipe.

A 320 kilometers transmission line will extend from Kennett power plant to a substation near Antioch at the power load center for northern and central California. This 220-kv. 3-circuit line will require 1,200 double and 1,510 single circuit towers (9,100 tons of steel) 6,850 tons of copper conductor, and 220,000 insulators.

The Sacramento-San Joaquin delta cross-channel extends 38.60 kilometers from a dam and locks near Hood on Sacramento river 33.80 kilometers

below the city of Sacramento to the junction of Mokelumne and San Joaquin rivers. Width of the artificial cut is 38.20 meters and the canal capacity is about 283 cubic meters per second. Major construction items are: excavation 321,000 cubic meters, structural steel and gates 1,360 tons, steel sheet piling 900 tons, wooden sheet piling 3,000, round wood piles 20,000. These works will provide for introducing additional water supplies furnished by Kennett reservoir into San Joaquin delta for salinity control and delta use and diversion by the Contra Costa conduit and San Joaquin pumping system.

Contra Costa conduit, along the south shore of Suisun Bay from near Knightsen to Martinez and Walnut Creek, will take a pumped supply from freshwater channels of the San Joaquin delta. Eighty kilometers of canal ranging from 3.40 to 0.57 cubic meters per second capacity, 10 kilometers of 0.457 meter diameter pipe line from Bay Point to Martinez and six booster pumping plants are required. Besides 15 pumps, this conduit involves about 950 tons of steel pipe, 513,000 cubic meters of canal excavation, 50,000 square meters of concrete canal lining, 57 highway and 129 farm bridges, 2,320 meters of flumes, etc.

The San Joaquin pumping system, total length 265 kilometers, extends from the junction of the Mokelumne and San Joaquin rivers to Mendota and is in three units, namely; delta channels, Mokelumne river to No. 1 pumping plant—48 kilometers; San Joaquin river channel, No. 1 pumping plant to Merced river—116 kilometers; constructed canal, mouth of Merced river to Mendota—101 kilometers. The system is considered as in two sections, the first on lower San Joaquin river comprising a series of five dams and pumping plants, delivering by successive lifts from tide water to elevation 19.0 meters at Hills Ferry 139 kilometers above Stockton. Capacity of the pumping plants will be from 56.50 to 85.0 cubic meters per second installed in 14.20 cubic meters per second capacity. The five steel dams, lengths 73 to 104 meters will be collapsible and capable of passing flood flows. The second section will be a concrete-lined canal 9.78 to 8.55 meters bottom width, containing five pumping plants and extending from the pool above No. 5 plant on San Joaquin river to Mendota, lifting water to 55.0 meters maximum elevation above sea level near Los Banos.

Major construction items in the San Joaquin pumping system are:

Delta channel excavation—3,060,000 cubic meters; River embankment—396,000 cubic meters; River channel excavation—1,285,000 cubic meters; canal lining 2,260,000 square meters; Canal excavation—4,750,000 cubic meters. Dam excavation—27,600 cubic meters; concrete—7,200 cubic meters; steel sheet piling 1,900 tons; steel leaf gates and struts—750 tons; structural steel—400 tons; traveling cranes—5. Pumping plants excavation—112,500 cubic meters; concrete—416,000 cubic meters, structural steel—150 tons; motors and pumps—each 49.

A 110-kv double circuit transmission line 153 kilometers long will be built from Kennett terminal substation to No. 10 pumping plant near Los Banos. These works will furnish water to lands now irrigated from San Joaquin river. The plan is to divert the river into the Frien-Kern and Madera canals

at Friant dam, 98 kilometers upstream and 98 meters higher elevation than Mendota.

Friant reservoir on San Joaquin river in Madera and Fresno counties requires a gravity concrete dam about 1.6 kilometers above Friant. Reservoir capacity totals 493,410,000 cubic meters, of which 333,050,000 cubic meters are effective storage, and the reservoir has a surface of 1,705 hectares, with a length of 22.50 kilometers. The dam is 77 meters high above low water with 1.53 meters freeboard, 1,160 meters long on the crest and 58.0 meters thick at the base. Net spillway length is 137 meters and depth of spillway 4.58 meters. There are six irrigation outlets 2.44 to 1.98 meters in diameter. Construction items include 331,000 cubic meters of excavation; 1,018,000 cubic meters concrete; 310 tons of steel pipe; 770 tons of steel drum gates; 1,700 hectares of clearing, etc.

Friant power plant, at the downstream toe of the dam, has two generating units, each consisting of an 18,000 horse power turbine served by a 2.44 meter diameter penstock and a 12,000 kilowatt generator. Power plant capacity is 30,000 kva. Besides the hydraulic and electrical equipment Friant power plant will require 6,100 cubic meters of excavation; 7,500 cubic meters of concrete; 530 tons of steel pipe and trash racks; 725 tons of valves; 65 tons of structural steel, and other items.

Madera canal, extending 56 kilometers in Madera County from Friant dam to Chowchilla River, will have a capacity of 42.50 to 14.20 cubic meters per second, the bottom widths ranging from 4.28 to 2.60 meters. This canal will deliver by gravity to irrigated and producing lands which are now deficient in water supply. The work includes 975,000 cubic meters of canal excavation; 100,000 cubic meters of structure excavation and fill; 247,000 square meters of rock trimming; 735,000 square meters of canal lining; 5,500 cubic meters of structure concrete; 950 meters of 0.915 meters diameter concrete pipe; eight siphons with lengths of 97.50 to 463.0 meters and diameters of 2.75 to 4.13 meters; 12 bridges for county and secondary roads; and other items.

Friant-Kern canal, in Fresno, Tulare and Kern counties, will have a length of 253 kilometers from Friant dam to Kern river and a capacity of 85.00 to 42.50 cubic meters per second. A 0.57 cubic meters per second auxiliary pumping system will serve a small developed area above the East Side canal in Kern county. Bottom width of the new canal in sidehill section is 6.70 meters throughout, varying in flat topography from 9.75 meters at Kings river to 7.05 meters at Kern River. Two tunnels, one 6.10 meters in diameter by 428 meters in length and one 7.0 meters diameter by 91.5 meters, eleven main siphons 7.00 to 5.80 meters diameter, 22 railroad, highway, and cross-road siphons; 174 precast concrete pipe underdrains from 0.61 to 1.53 meters double; and other structures are required. Canal works involves 6,000,000 square meters of concrete lining; 62,000 cubic meters of structure concrete; 8,880,000 cubic meters of excavation; 7,600,000 cubic meters of rock trimming; and 1,085,000 cubic meter structure excavation and fill.

The many varied benefits from construction and operation of the Central

Valley Water Project are not only local and state, but national as well. Navigability of the Sacramento river will be restored for some 400 kilometers from its mouth to Red Bluff by furnishing regulated flow coupled with additional open channel improvements. Lands under irrigation along Sacramento river will receive a dependable and assured water supply in all seasons and, together with urban centers, will enjoy a large additional protection from floods on the river. Higher water levels maintained in the river will reduce pumping charges for irrigation water drawn from the stream and dependable water supplies will be assured municipalities along the river.

The Sacramento-San Joaquin delta will be freed from the saltwater menace and will have ample suitable water supply for irrigating its 160,000 hectares of fertile and producing lands. Extensive and important manufacturing industries and agricultural areas in Contra Costa county will obtain adequate and dependable supplies of fresh water. Navigation on San Joaquin river can be restored for 138 kilometers above Stockton by incorporating locks in the five dams of the San Joaquin pumping system.

Irrigation supplies drawn from San Joaquin river will benefit by reduced pumping charges resulting from higher water levels. An adequate supplemental water supply will be furnished 160,000 hectares of highly developed, settled, and producing lands in upper San Joaquin Valley. Hydroelectric power generated at Kennett and Keswick dams, utilizing water released into Sacramento river for navigation, irrigation, and salinity control, will be transmitted over the Kennett power line to a market load center for distribution to domestic, industrial, municipal and agricultural consumers.

The cost of the project is estimated to be \$170,000,000 but its proponents claim its economic value to California cannot be estimated in dollars and cents. In the Sacramento Valley spring floods which now flow down the river and occasion constant expense in the maintenance of levees and dikes in the lower valley, instead of being wasted into the ocean, will be impounded behind Kennett Dam and released through the period of low water in the summer to obtain a constant stream of not less than 141.50 cubic meters per second in the lower Sacramento. It is expected that not only will this assure a channel 1.83 meters deep to Chico Landing and a minimum of 1.22 meters to Red Bluff but also the additional water released throughout the summer season will maintain higher levels which will reduce pumping costs to the farmers and ranchers in the lower valley who pump water from the river over the levees and into their irrigation canals and laterals.

In the rich delta country adjacent to San Francisco Bay, present diversion of fresh water in the upper valley has created a menace of salt water penetration of these agricultural lands due to the backing up of salt water from San Francisco Bay into the river channel. The increased flow from the Sacramento would insure that the bays and sloughs of the delta country will again become fresh water and will permanently restore 160,000 hectares of fertile land to a maximum productivity. Another major economic

benefit is the assurance of an adequate fresh water supply in the industrial area on upper San Francisco Bay. This supply of fresh water tend to reduce costs to present industries operating there and might attract additional industries depending upon an adequate fresh water supply for their processes.

Similar benefits are to be gained from the San Soaquin Valley. In addition the two canals running north and south respectively from Friant reservoir will rescue 80,000 hektares of the southern San Joaquin Valley from a return to the desert (Steppe). Navigability of the San Joaquin as mentioned will be possible for about 140 kilometers above Stockton.

The before-mentioned cost figure of the project does not include the cost of relocating the highway and Southern Pacific Railroad in the upper Sacramento Valley. The relocation of the railroad grade for many kilometers in this mountainous territory will be expensive, the cost being estimated somewhere in the vicinity of \$30,000,000.

The Division of Water Resources has carried out a number of major studies covering other sections of California regarding their water supply problems. Projects planned in detail or actually under way for additional water supplies for the South Coastal Basin will cost in the aggregate in round figures close to \$350,000,000. Distribution systems will add much more to this cost but plans for these have not yet been studied in detail and await more comprehensive knowledge than now exists.

Additional supplies may come from the following: (a) Salvage of local flood waters; (b) Salvage of local evapo-transpiration losses; (c) Salvage of sewage waste; (d) Importation of water from Mono Basin and from Colorado River (The two last-mentioned now fairly well advanced toward successful completion).

South Coastal Basin consists of Santa Ana, San Gabriel, and Los Angeles River Valleys, and the West and South Coastal Plains. It is 145 kilometers long at its maximum and 80 kilometers wide, containing 5,700 square kilometers of irrigable or inhabitable land and has a population of well over two- and one-half million. The total of all water it is proposed to import and the total of all local water it may be possible to salvage gives a quantity, which, spread over the entire 5,700 square kilometers would cover it 0.30 meter deep. Of this, slightly more than 20 per cent may be furnished by salvage of local waters. With proper distribution this quantity of water is probably sufficient for ultimate needs so far as the future may be visualized (Bull. 32).

The increase in the use of water has been rapid for some years back, but the past, especially in the territory to the east of the Metropolitan Area is not necessarily indicative of future rate of growth. More than half of the present annual increase is in the Metropolitan area, comprising the western 40 per cent of the Basin. In the Agricultural Area, which term may be applied to the eastern 60 per cent, total annual increase in use is less than in the Metropolitan area. If importations for Los Angeles city from Owens Valley be neglected, about 90 per cent of all water supplies are derived from underground reservoirs underlying the valley floors on

which the major part of the cities and towns and agricultural areas have been developed. The underground reservoirs or basins in turn get their supply by retaining a part of the wild and sudden floods of the region and a part of the rainfall which comes upon the valley floors overlying them. They regulate, by natural processes, the surplus waters of the west for use in the dry years and have made the present economic development of the region possible. All plans for additional water supplies propose further utilization of the underground reservoirs and control, in so far as possible, of the supplies placed in them.

If the entire South Coastal Basin were a single underground reservoir the matter of further utilization would be comparatively simple from the physical standpoint. Preliminary estimates indicate for the basin as a whole that the longtime average replenishment, including present importations from Owens Valley to Los Angeles, is about equal to the present draft, but a statement to the effect that replenishment equals demand would be misleading and in fact in some basins, even if long time supply does equal demand, the situation is precarious for other reasons. Preliminary studies indicate that instead of one simple basin there are 29 separate units or underground reservoirs and that each one is a problem which must be studied separately. A few of these basins apparently have a surplus, considering the longtime average replenishment. The others are overdrawn in varying degrees but legal, financial and physical barriers to general transfer of supplies from one to the other are almost insuperable, so that any estimate of present shortage must disregard the surpluses and combine the shortages in individual basins. On this basis, preliminary estimates place the aggregate present shortages in the agricultural area, or eastern two-thirds or between 247 and 308 million cubic meters.

Many agencies are at work on varied activities directed toward conservation of local wastes and to a better understanding of the local situation. Two agencies are directing their activities toward importing additional supplies. The City of Los Angeles is bringing additional water from Mono Basin and this of course, belongs exclusively to the city and cannot be used outside. The Metropolitan Water District is organized to bring in water from Colorado River and is actively proceeding toward that end as noted elsewhere. Its legal setup is broader than that of Los Angeles city and its plans are especially important to the people of the South Coastal Basin.

To the west, lying between Los Angeles and Santa Barbara counties is Ventura County with a population in 1930 of 54,976 entirely concentrated in the arable areas. Buenaventura or Ventura, as it is usually called, the county seat with a population of 11,603 is supported largely by the oil industry. Santa Paula and Fillmore are principal towns of the citrus area and Oxnard is the center of the sugar beet industry. Ojai is the principal town of the Ventura River Basin. Rainfall is scanty, 305 millimeters at Oxnard, 518 at Piru, 335 at Ojai and 396 at Santa Susana. In the mountains it varies from 275 to 915 millimeters with some snow at higher elevations which quickly melts. There are two seasons, wet

and dry with 78 per cent of the precipitation from December to March inclusive. Most of the irrigation supplies are procured by wells sunk into the alluvium of the valley fill, but in the Santa Clara River system and Ventura River system there is a small summer discharge which is diverted from gravity irrigation.

In this region the State Division of Water Resources initiated a 5-year investigation in 1927 to resolve a conflict caused by filing of applications to appropriate water from the extreme headwaters of Sespe Creek to convey it to lands in Ventura River Basin and also by similar proceedings for taking water from Sespe and Piru Creeks to convey water to lands in the Calleguas Creek Basin near Moorpark. The irrigated area in Santa Clara River Valley has grown from 10,000 hectares in 1909 to 43,000 hectares in 1932 about equally divided between citrus and walnut groves which both pay high water prices.

The rainfall in the region is erratic, when the investigation started it was below the 40-years average later increasing to from 15 to 35 per cent above. The discharge of the Santa Clara River, the principal stream of the county, wasted about 70 per cent of its runoff into the ocean and the Ventura River, the next in size wasted as much as 90 per cent into the ocean. Numerous reservoir sites exist on tributaries to Santa Clara River but the costs were found to be excessive for their development in view of the fact that the maximum year of rainfall was 40 times the minimum year while for the 10-year period 1923-1932 it is estimated to be only 60 per cent of the long time average. Studies were also made which would accomplish conservation of the water by utilizing space in underground reservoirs of Piru Basin in Santa Clara River Valley and Montalvo Basin in the Coastal Plain. Spreading grounds are proposed in these two basins to cause water which now wastes into the ocean during floods, to percolate to the water table.

In view of the excessive cost of creating surface storage reservoirs, consideration was also given to pumping in the lower Santa Paula Basin. This would create additional underground reservoir capacity and conserve water by killing the willows now growing there, thus making a large part of the present annual waste of 14.8 million cubic meters available for use. Estimates indicate it would cost four times as much to conserve this volume of water by surface reservoirs as it would by creating underground capacity. The cheapest step in conservation of Santa Clara Valley water was found to be the construction of the Montalvo spreading works and next a pumping project in Santa Paula Basin and a conduit to Pleasant Valley. For the Ojai Valley no construction would be immediately necessary, importations from Ventura River or Sespe Creek would be too costly. The yield of the upper Ventura River could probably be improved by pumping the basin and installing spreading works. We see that in most cases in southern California this type of storage is gaining in favor due to suitable geologic conditions.

The northern part of the Santa Clara Valley embraces a gross area of 54,000 hectares extending from the south end of San Francisco Bay to

Coyote—the Station on the Southern Pacific Railroad and laterally to the foothills east and west. Between the mountain and foothill areas immediately above lies a valley of 138 square kilometers which is dependent for its water supply upon runoff from the mountain and foothill areas and local precipitation. The major contributors to the water crop of the lower valley and the most important sources susceptible of further development are Coyote River, Guadalupe River, Alamitos Creek, Los Gatos Creek and Stevens Creek. The drainage areas of these streams reach well into the mountain sections and comprise the area of 1,110 square kilometers of watershed of more abundant precipitation.

The ground water situation in the valley is one that has commanded the attention of thoughtful residents for many years and in 1926 the Santa Clara Conservation Association was formed and did some spreading of waters in an effort to increase the normal contribution to ground water. This ground water level in Santa Clara Valley, exclusive of the former artesian zone north and west of San José receded 29 meters between the spring of 1915 and 1933. This recession probably indicated a decrease of approximately 900 million cubic meters in available ground storage during the 18-year period. The rainfall after 1915 was scanty and resulted in diminished stream flow. The disturbance of the factors of overdraw and of scanty rainfall established a new lower ground water level.

At this point might be mentioned that the heavy pumping draft during the past 25 years is considered to be the cause of the subsidence of the region actually taking place. First noted about 1920 when the U.S. Coast and Geodetic Survey checked the elevation of benchmarks set in 1912, and since continuing, an area of more than 1,300 square kilometers is subsiding (Stohnset, 1937). At the southern end of San Francisco Bay the settlement is slight; 60 and 25 millimeters total at Warm Springs and Irvington respectively, on the east side of the bay; 130 and 0 millimeters total at Palo Alto and Redwood City respectively, on the west side of the bay having been observed. The southern end of the valley has subsided much more, the maximum in the 1912-1936 period reaching 1.57 meters at the Hall of Records within the City of San José (population 80,000). Seismic movements on the nearby San Andreas fault have been mentioned as the cause but local opinion does not ascribe the subsidence to seismic causes, other explanation being preferred, such as the fact that some soils shrink when water is drained out of them and as stated above the water table in the San Jose region has been considerably lowered by pumping.

Pumping drafts upon ground water of the valley had increased materially in years immediately before 1915 and since that time roughly from 31 million to an average of 165 million cubic meters per annum. This in itself would have caused a substantial lowering of the ground water level even had the precipitation and natural recharge been normal. The total mean annual discharge of surface streams at the rim of the valley during a period of normal rainfall is estimated to approximately 213 million cubic meters, of which roughly 41 percent from the Coyote, 17 percent from the Los Gatos, 15 per cent from the Alamitos and Guadalupe, 4.5 per cent from the Stevens,

11 per cent from other minor west side streams and 11 per cent from minor east side streams. The mean annual surface waste of these streams into San Francisco Bay during a period of normal rainfall is estimated to approximately 128 million cubic meters but of this a considerable portion originates on the valley floor below where it is impracticable to conserve it.

The State Division of Water Resources initiated and concluded an investigation into the water situation of the Santa Clara Valley, this work being completed in 1933. The investigation found an area of about 40,000 hectares being irrigated in the valley dependent in whole or in part for irrigation supply upon the underlying ground water storage basin. It finds that ground water levels can be raised and reserve storage increased by stimulating additional percolation either by spreading stream flow in the natural streams through the operation of surface reservoirs which would hold back flood crests normally escaping to the ocean, until reduction of flow in the stream of the valley gives an opportunity for the absorption of reservoir releases. Conservation of these surface wastes from streams debouching into and traversing Santa Clara Valley affords, the Division finds, the best means of restoring ground water level, and it is doubted that the importation of water from any foreign source would be necessary or economical.

Prior to settlement by whites, the Pit River region was inhabited by the Pits and the Modocs, warlike tribes of Indians, who were responsible for many raids and massacres of emigrants passing through the territory on their way to Oregon or the California gold fields. No general movement toward settlement of the region was made until after the close of the Modoc Indian Wars in 1873 (Zander, 1933). The first settlements were made on the Pit River in about 1870-71, in the vicinity of Likely and in Big Valley. Abundant growth of grasses in the meadows adjacent to the streams and other conditions favorable to stock raising ever since predominating attracted them.

There are approximately 120,000 hectares of agricultural land in the upper Pit watershed of which about 30,000 are now irrigated. The adequate irrigation of the present lands and the 90,000 hectares of dry land would require the entire water crop of the drainage basin. The only conservation project of magnitude which appear presently feasible are for developing sufficient water to round out the irrigation requirements of lands now irrigated in South Fork and Big Valleys. Reservoir sites are to be found. Stream administration is an important means of conserving the water supply of the stream system, by the prevention of unnecessary waste, and such a plan has been evolved after the State Division of Water Resources was consulted.

The total length of channel of the upper Pit River from the head waters of the South Fork to the Shasta-Lassen county line is 210 kilometers. The gradient is rather steep, elevation of river at the lower line being 687 meters at Alturas 1,325 at Jess Valley, 1,540 meters. Average valley floor elevations are: Big Valley 1,265, Hot Springs Valley 1,310, South Fork Valley 1,330, Jess Valley 1,555 meters. The elevation of the broad undulat-

ing plateau of Devils Garden is approximately 1,555. Geologically the upper Pit region is situated on the western fringe of the Great Basin. Its climate, topography and geology are characterized by the general features common to that area; namely, semiarid undulated plateaus interspersed with mountain ranges and with lava rocks and ancient lake beds predominating. To relieve water shortage some 53 reservoirs with an aggregate capacity of about 173 million cubic meters have been constructed within the watershed. These range in size from the Big Sage of 95 million cubic meters down to such of 6,000 cubic meters. They are used principally to furnish water for stock and to supplement irrigation water.

VIII. Boulder Dam and Southern California.

Rational economic advancement of southern California and the Pacific South-west underlies the inception of the Boulder Canyon Project and the construction of the gigantic dam at Black Canyon on the Colorado River. First and probably more important is flood control. By regulation of flow provided for by the Lake Mead storage behind the dam, the threat of disastrous floods will be removed from the rich irrigated districts in the extreme south-eastern portion of California, notably among which is the Imperial Valley.

The second sound objective of the Boulder Canyon project is the storing of water and delivering thereof for the reclamation of land and other beneficial purposes within the territorial United States. Probably the most beneficial aspect of this provision in relation to the economic development of the Pacific South-west is the stipulation giving Los Angeles and adjacent cities a continuous flow of 42.50 cubic meters per second of water to augment their present supplies. The unprecedented growth of population in the southern California Coastal Plain in past years has necessitated a development of approximately 80 per cent of the natural water supply contiguous to that area. The deficiency in local waters had become a matter of serious concern and is now alleviated by the Colorado River allotment, which should provide an ample supply for many years to come. This insurance of an adequate water supply will permit uninterrupted commercial and industrial expansion not only of the Pacific South-west but of California as a whole, water being indispensable to the development of this region.

Also important, in connection with water supply and as a correlated part of the Boulder Canyon project is the All-American Canal which provides for a main canal 128 kilometers long connecting the Colorado River with the Imperial Valley and 210 kilometers of branch canals supplying an arable area of approximately 400,000 hectares. Third factor leading to the construction of the Boulder dam is the generation of power, revenues from which are expected to supply most of the income needed to make the project a self-supporting undertaking. When it is considered that electrical energy is to be purely a byproduct of released storage as dictated by ir-

rigation and other requirements, the feasibility of this objective is a matter of much conjecture by many economists and engineers.

Topographically the Colorado River Basin is naturally divided into three different parts. The south-western part is in general but little above the level of the sea, though isolated mountains rise here and there to elevations of thousands of meters. The central part is a great plateau region which has a general elevation of 1,500 to 2,500 meters. This part is bounded on the east and west by ranges of high mountains, and most of it is cut by deep gorges and canyons. The northern part of the basin is bounded on the east by the Rocky Mountains, which rise to elevations of more than 4,300 meters; on the north by the Wind River Mountains, in Wyoming, which reach 4,180 feet or more, and on the west by the Wasatch Mountains, in Utah, which reach altitudes exceeding 4,000 meters.

The differences in topographic features of the basin at once suggests great differences in the climate. In the south-western desert region the average annual precipitation ranges from 40 to 200 millimeters and the temperature from about 0°C in the winter to 49°C in the summer. In the central part of the basin the average annual precipitation ranges from about 250 millimeters over most of the plateau area to about 760 millimeters in the higher mountains, and although temperatures of 38°C are not uncommon during the summer, the winter temperatures in exposed places drop below zero. The northern part of the basin, which includes the major areas of high mountains has a mild summer climate but very severe winters. Temperatures of -35°C are not uncommon, and the annual precipitation ranges from less than 250 millimeters along Green River to as much as 1,525 millimeters along the Continental Divide. These differences as given explain why 76 per cent of the annual discharge of Colorado River at Yuma originates in that part of the basin above and including Green River (LaRue, 1925).

Hydrologically, the Colorado River, draining a basin of 625,000 square kilometers is noted for a tremendous volume of flow, sudden and severe floods, and the extremely high silt content of the water. From records over a 34-year period the annual average flow has been estimated at 22,203,360,000 cubic meters annually. During this period the minimum flow at Yuma, Arizona, was 8,634,640,000 cubic meters annually and the maximum flow 30,838,000,000 cubic meters. In this connection it is interesting to note that for the first nine months of 1934 the recorded flow was 4,587,460,000 cubic meters, or less than 20 per cent of the average for the 32-year period immediately preceeding. On the other hand the 1884 discharge at Yuma was more than 2,830 cubic meters per second for 57 days and the annual runoff was about 39,472,640,000 cubic meters. A maximum of at least 7,080 cubic meters per second at Bright Angel Creek was found and referred to a well-defined rating curve by the United States Geological Survey. Waterlodged drift 13 kilometers below the mouth of Diamond Creek indicates a discharge of 5,600 to 6,230 cubic meters per second.

The Boulder dam is built at the Black Canyon dam site located down-

stream from the originally selected site after which the dam is named, the rock conditions of the canyon walls having been found more satisfactory for a high dam at the lower site. The location is south of the sharp bend in the river shown on all maps and is near latitude 36°N. , 518 kilometers by the river above Yuma. The stream bed elevation at the upstream face of the dam is 105.20 meters and the water surface elevation of Lake Mead with the storage filled is 374.84 meters above sea level, making the maximum depth of water at the upstream face of the dam 179.64 or in round figures 180 meters. Crest of dam is at elevation 375.76 and lowest foundation at elevation 154.33 meters above sea level making total height of dam 221.43 meters maximum and with a freeboard of 0.92 meter with storage filled.

The 1935 completed dam will impound a reservoir having a capacity of 37,622,360,000 million cubic meters. Of this reservoir 11,718,440,000 cubic meters must be reserved at all times for storage of flood waters of the river, 6,167,600,000 cubic meters capacity have been set aside as a silt storage behind the dam, and from 14,802,240,000 to 18,502,800,000 cubic meters is considered as active storage for irrigation, power and public water supply. As previously mentioned, power will be generated only as a by-product of the waters released from storage in accordance with the following program of water allocation.

Claims of various states on the usage of Colorado River water at times presented almost insurmountable obstacles to the sponsors of the Boulder Canyon project. When the claims of six states had been adjusted satisfactorily the project started, although Arizona is opposed to certain provisions regarding the allocation of water and power rights.

According to present contracts Arizona will be entitled to 3,453,856,000 cubic meters, Nevada is entitled to 370,056,000 cubic meters, and California has been allocated 5,427,488,000 cubic meters, 42.50 cubic meters per second or approximately 25 per cent of that volume being reserved for the exclusive use of the Metropolitan Water District which will take its share from the reservoir behind Parker dam now actually under construction about 145 kilometers below the Boulder Canyon and Lake Mead storage. The remainder of the California allocation will be taken by the various irrigation districts. Under this agreement, the price paid by the Metropolitan Water District for its allotment will be 20.3 cents per 1,000 cubic meters (25 cents per acre feet). In making these allotments no consideration has been given to possible claims from Mexico for stored water.

The power to be generated in releasing this volume of water to the Boulder Dam turbines under the average head of 161.50 meters is expected to be equivalent to 4,240,000,000 kilowatt hours of firm power and 1,500,000,000 kilowatt hours of secondary power. Through the provisions of the original Boulder Dam contracts this power will be assigned as follows:

Metropolitan Water District Aqueduct	1,526,500,000 kvh
State of Arizona	753,200,000
State of Nevada	753,200,000
City of Los Angeles	551,200,000
Southern California Edison Company Ltd.	381,000,000
Pasadena, Glendale, Burbank	254,000,000

It is expected that the output of secondary power will be absorbed by the Colorado River Aqueduct pumping plants of the Metropolitan Water District, which will require ultimately approximately 275,000 kilowatt.

Power from Boulder Dam is delivered to the various distributional agencies on the high side of the transformers, the price for firm power being 1.63 mills per kwh; and for secondary or dump power 0.5 mills per kwh, transmission facilities to be furnished by the purchaser. On this basis the revenue from power sales would be \$7,057,900 from primary power and \$275,000 from secondary power, assuming full utilization of the plant output.

Provisions also stipulate that in the event that Nevada and Arizona are unable to use their share of the power, it will be divided equally between the City of Los Angeles and the Southern California Edison Company until such time as those two states can utilize the energy economically. Of this there is little immediate prospect and it appears that the City of Los Angeles and the Southern California Edison Company would be obliged to take the power.

The advent of over 4,000,000,000 kwh of firm power in the area within a 500 kilometers radius of Boulder Dam will have a tremendous economic significance both in the territory and on the electrical industry. Within this 500-kilometers radius are 13 California counties having a population of 3,332,000 people, eight Arizona countities of approximately 35,000 and thirteen Utah counties with a population of approximately 125,000. In 1935 the population of this region represented roughly 1,000,000 domestic electric consumers including electrified farms, 123,241 commercial and small power customers and 22,772 wholesale or large consumers. To these customers the electrical utilities sold 2,800,000,000 kwh directly, and in addition sold 240,000,000 kwh for street lighting. Losses and company use brought the total generation in 1933 in this area to almost exactly 4,000,000,000 kwh.

Generating facilities at the present time total 1,444,277 kilowatt. At a load factor of 40 per cent, these generating facilities are capable of producing roughly 5,000,000,000 kwh or 1,000,000,000 in excess of the amount required in 1933. With the addition of firm power from Boulder Dam, exclusive of the Metropolitan water District requirements, the present per capita generation of 1,200 kwh in this territory will be increased to approximately 2,000 kwh per capita should it be possible fully to utilize the output of Boulder Dam by 1939. This figure does not include the present surplus of roughly 1,000,000,000 kwh now existing in the area.

The Parker Dam on the Colorado River is located about 240 kilometers below the Boulder Dam and is to form a pondage for the intake to the aqueduct of Los Angeles Metropolitan Water District. The storage will be 863,464,000 cubic meters and provision is being made for future power development. The dam consists of a concrete arch about 100 meters high above foundation and is unique in that only about 25 meters or one-fourth of the total height will be visible above water surface when completed, and the remaining 75 meters being below streambed which requires an un-



Parker Dam, Colorado River, California-Arizona. Diversion to Los Angeles Metropolitan Water District. Conduit 420 Km of which 150 Km Tunnels. Dam excavation carried 75 m below river bed. View shows concrete poured 25 m with still 50 m to river-bed. Above Trashrack Structure to Conduit Intake. Completed 1938.

Courtesy United States Bureau of Reclamation, Washington, D.C.

precedently deep dam excavation of 75 meters or more showing the depth of sediment accumulated above solid rock in that section of the river. Crest elevation will be at 122 meters above sea level and the roadway bridge of 138.77 m. The river is diverted for construction through two tunnels capable of taking a flow of 1,700 cubic meters although the flow since diversion has been only from 113 to 200 cubic meters per second. The dam excavation is 1,150,000 cubic meters and the concrete in the dam will be 200,000 cubic meters. The damsite is located about 24 kilometers upstream from the town of Parker, Arizona near the easternmost point of California on the river.

The All-American Canal as its name implies is to be located entirely on United States territory whereas the present Imperial Canal now supplying the Imperial Valley with irrigation water after leaving the intake at an intake near Yuma leads into Mexico and then farther west turns north to return into United States and to the Imperial Valley and Salton Sink region. The All-American Canal will leave the Colorado River immediately below the Imperial Dam built on the river about 32 kilometers upstream from Yuma, Arizona. This location is about 240 kilometers downstream from Parker Dam just described. At the diversion are also located the desilting works.

The main canal connecting the Colorado River with the Imperial Valley has a length of 128 kilometers and is designed for a maximum capacity of 425 cubic meters per second with a velocity of 1.145 meters per second. During several years of initial operation the flow is expected to be as low as 190 cubic meters per second or 45 per cent of ultimate capacity flow. The initial diversion of 425 cubic meters per second includes 56.50 cubic meters to be taken out at Siphon drop for the Yuma project and 85.00 cubic meters to be diverted at Pilot Knob, 11 kilometers west of Yuma for power development. Power plants at Pilot Knob and at four drops on the canal will allow for the development of 85,000 horse power of which 47,000 horse power is firm power. No power will be developed at Imperial dam. The canal diverts at the Imperial dam at an elevation of 54.75 meters dropping to an elevation of -3.05 meters at its westerly end. It has a maximum section of 61.00 meters at the water surface and 40.80 meters at the bottom, with a water depth of 6.70 meters. The main canal for 16 kilometers will pass through a ridge of shifting sands into which the deepest excavation is 30 meters. To prevent blow sand from drifting into the canal four means are considered. These are: growing vegetation in a zone on each side of the canal, covering the dune sand with coarser, excavated material, spraying the sand with crude oil, maintaining a 4.60 meters wide berm on each side of the canal at the level of the mesa floor. None of the main canal of 128 kilometers will be lined although some of it may require a compacted earth lining. This main line of the All-American Canal was authorized in the Boulder Canyon Project Act of December 21, 1928 to irrigate more than 400,000 hectares in the Imperial Valley and Coachella Valley and \$38,500,000 of the \$165,000,000 project was allotted to cover the cost of the work.

The Coachella branch canal which diverts from the main canal about 57 kilometers west from the Imperial dam at the westerly edge of the sandhills runs in a northwesterly direction along the border of the Salton Sea. It is 200 kilometers long from the diversion from the main canal and to the end on the west side of Coachella Valley at the county line. This canal has a capacity of 56.50 cubic meters per second where it takes off from the main canal and of 28.25 cubic meters per second where it enters the Coachella Valley at the north-west end of Salton Sea. Canal drops are provided at which power will be developed in the future when needed. This canal will supply 27,500 hektares of the East Mesa and 2,760 hektares of the Dos Palmas Area, the remainder of the East Mesa being irrigated by laterals from the main canal. The Coachella canal takes off from the main canal at elevation 50.00 meters approximately and drops to elevation —30.50 meters along the Salton Sea. It may be lined with concrete from kilometer 133 to the end, this section extending along the margin of Coachella Valley, with considerable slope toward the valley. Lateral ditches in the valley may be lined, except in clay soil. Part of the water supply will be obtained by pumping from underground. These economies permit the limitation of capacity of the canal to 28.25 cubic meters per second where it enters the valley near Dos Palmas.

Irrigable areas in the Imperial Valley and the Coachella Valley are as follows:

Divisions	Gravity hektares	Pumping hektares	Total hektares
Imperial Irrigation District	211,248		211,248
East Mesa	79,150	985	80,136
West Mesa		50,945	50,945
Dos Palmas	4,232		4,232
Coachella Valley	46,585	15,396	61,981
Totals west of Sand Hills	341,215	67,326	408,542
Pilot Knob Mesa		9,045	9,045
Grand Total	341,215	76,372	417,587

The City of San Diego has been allocated 4.40 cubic meters of water for domestic supply and is considering having it carried through the All-American Canal and the Imperial Irrigation District and taken out on the west end of the Imperial Valley, lifting it more than 1,200 meters, with power from Boulder Dam, and delivering it to the coastal plain in San Diego county.

The main canal extends across the Imperial Valley near the international boundary and to the present West-Side canal 128 kilometers from the Imperial Dam. The Coachella as stated takes off just west of the Sand Hills and runs in a north-easterly direction along the border of the Salton Sea to Dos Palmas where it enters the Coachella Valley which it crosses near Indio from which point it turns south along the west side of the valley to its end.

The East and West mesas, the Dos Palmas area, and the greater part of Coachella valley are desert lands with no improvements. In Pilot Knob

mesa are large tracts of irrigable lands, with pump lifts of 25 to 70 meters from the canal. Transmission and operating losses of water in this region are high running up toward 25 per cent of the diversion of the Imperial Dam.

Most important and novel of the elements at the Imperial dam and diversion intake are the desilting works equipped with circular scraper mechanisms designed to remove a large part of the 55,000 to 65,000 metric tons of silt per day which experiments and estimates indicate would otherwise be carried into the canal and entail a yearly cost probably in excess of \$1,000,000 to remove. Silt has been removed at Laguna rather successfully by intermittent operation of gates in a sluiceway at the end of a long skimming weir. Immediately below Yuma, near the Mexican border is the Imperial Canal head gates or Rockwood heading with no adequate desilting arrangements. Silt deposited in the canal and laterals of the Imperial Irrigation District cost annually \$800,000 for removal, which is the principal economic reason for the elaborate research and the decision of the U.S. Reclamation Bureau to build desilting works at the head of the All-American Canal.

The desilting works consist of six 79.00 by 234.50 meters settling basins set at an angle of 60° with the influent channels, to permit arranging the 38.00 meters circular scrapers to give minimum interspaces. Each basin has a rated capacity of 56.70 cubic meters per second with a maximum velocity of 73 millimeters. Provision is made for another pair of basins, to bring the total capacity to 454 cubic meters per second. Velocity in the influent and effluent channels is 1.83 meters per second and between the basins 2.14 meters per second. Controlling the water entering the influent channels leading to the desilting basins are four 23 meters long rolling lift gates 4.27 meters in diameter and 7.00 meters high to the top of the flash weir. Headgates for the future Gila Valley canal are located at the east end of the overflow section of the Imperial dam. A maximum discharge of 4,250 cubic meters per second is cared for in the design of the dam or about three times the expected maximum flow. The depth of sediment being too deep for a foundation to rock the dam is a hollow reinforced concrete type 366 meters long in overflow section and 540 meters long at the elevation of the overflow crest 55.00 meters above sea level.

Standing on top of the Boulder Dam, or better on a higher point of the canyon rim, looking into the much publicity given "turquoise waters" of Lake Mead above the dam and the "crystal clear" stream emerging below it one comes to seriously question the necessity of the desilting works at the headgates of the All-American Canal. From where are the 60,000 tons of silt per day to come which the desilting works are designed to remove? This matter has been discussed (Vetter, 1937), showing the reason for desilting works.

Between the time of closure of the free outlet gates at Boulder Dam on February 1, 1935 and June 16, 1936, about 3,600,000 cubic meters of material have been eroded from the river bed between Boulder Dam and sampling station 16, at a distance of 21 kilometers below the dam. An

additional volume of 3,670,000 cubic meters have been eroded between stations 16 and 23, a stretch 50 kilometers long. The river having been relieved of its load above the dam here picks up a new load from the deep sediments and is in the progress of retrogression cutting itself a deeper channel and from the investigations and studies undertaken certain predictions have been made of the future silt load entering the Imperial reservoir.

The Parker reservoir with a storage of 616,760,000 cubic meters at lowest level might conceivably hold all the silt that will be eroded from the river bed between Parker and Boulder dams, a distance of 240 kilometers. Except at the rare occurrence of a flood in the Bill Williams River, a tributary to the Colorado immediately upstream from Parker Dam, the outflow from Parker Reservoir will probably be clear for many years to come. Below Parker Dam the clear water will pick up material from the river bed until the stream has become saturated with silt of the sizes available in the bed. The quantity of course material carried for a given discharge should be about the same as it was before the two dams were built; the fine material will be materially reduced. Where the river enters the Imperial reservoir and assuming a discharge of 5,100 cubic meters per second corresponding to an average runoff the quantities would be as follows:

Size in mm.	Total load in tons per day	
0.25—0.10	23,600	91,000
0.10—0.25	36,200	154,000
0.05—0.03	35,200	118,000
Totals	95,000	363,000

Since the total load varies approximately with the second power of discharge, intermittent greater flows will materially increase the load. At 1,230 cubic meters per second discharge the total load would, under these assumptions be 360,000 metric tons per day as shown in the second column under total load in tons per day.

It is expected that as progressive erosion takes place below Parker Dam the longitudinal profile of the river will become convex, starting below the dam with a very flat slope which will gradually become steeper and eventually reach a point where it is tangent to the existing slope of the river. Simultaneously with the change in profile, the Imperial reservoir will be silting up through a process similar to delta building at the mouth of a silt-laden river. The phenomenon has been carefully studied by the U. S. Reclamation Bureau by means of models at its hydraulic laboratory, Montrose, Colorado.

During the period of silting of the Imperial Reservoir the amount of course material passing the headgates of the All-American Canal will perhaps be small. However, the storage capacity to the sills of the headgates is only 26 million cubic meters, while as noted the average inflow of material coarser than 0.03 millimeter has been estimated at 95,000 metric tons per day, the total quantity entering the reservoir may be expected to be considerably in excess of this amount. Since 95,000 tons per day corresponds

to about 26 million cubic meters per year it is seen that within a relatively short period of time the accumulated silt in the reservoir may be expected to reach the sills of the headgates.

The present available knowledge of the laws of silt transportation does not permit consideration of degradation and other factors entering such as the change in size of material and change of slope but it is believed that during the first five years of operation of the canal more than 23,000 cubic meters of coarse silt per day will enter the All-American Canal headgates, when the rate of delivery is around 340 cubic meters per second. As the silt accumulates above the dam and the slope of the delta becomes steeper, the amount of silt reaching the headgates with a diversion of 425 cubic meters per second may eventually reach 46,000 cubic meters per day or 16.70 million per year. Using the same mode of computation it has been estimated that during the first ten years of operation a volume of approximately 60,000,000 cubic meters of silt will be entering the desilting works. During successive 10-year periods the volume may be more than doubled before eventually, the depletion of available material causes a reduction of the amounts carried into the desilting works. From the above, representing the most thorough studies and research by the Bureau of Reclamation, it is to be seen that the Colorado River will continue to be "too thick to drink and too thin to plow", at least along such stretches where it is given a chance to work along lines of its old behaviour.

Review and Summary.

The foregoing study has dealt with facts regarding the water conditions in California. In Part I the general relationship between geography and geology on one side, and on the other, points regards the regions water resources, their collection, conservation and utilization, particularly as regards their influence upon the works and structures falling within the field of activity of the hydraulic engineer to plan and erect were considered, also various important features of physiography as bearing upon development of water resources for public water supply, irrigation and hydroelectric power. The important rôle that economic geology and the geologist is called upon to play in all activities concerning water resources their conservation and utilization as well as in connection with the purely technical problems of the engineer engaged on such undertakings has been strongly emphasized, based upon the findings of other technical men as well as on the writers own experience during the thirty-five years activity on hydraulic engineering.

In Part II the physiographic, climatological, geological and other features of California have been briefly sketched according to authoritative sources and advanced standing of study in the various fields of scientific activity concerned. The results of research and experiments regarding evaporation, runoff, as well as physiographic and geological considerations regarding river characteristics of this particular region, have been discussed.

In Part III the water resources of the various physiographic regions of California have been discussed and according to the best and most recent studies and publications by State and Federal agencies. Public water supply, irrigation and hydroelectric power, the three great uses of water, have been covered at length, their individual peculiarities of requirement and their interdependence as related to the most rational conservation and utilization of the water resources of California were discussed. Flood control and the necessity for it has been shown by way of indicating the disasters that have gone over the land on occasions of extremely heavy precipitation of cloudburst nature. The prevention of these disasters and the only effective means of conservation of the runoff, by storage development, superficial or underground, was given consideration, especially the development of surface storage, whereas the equally or in some locations more, important development of underground storage, with its more favorable status regarding evaporation was more cursorily dealt with. These are the large features of water utilization in California, various others have been left alone.

Inland navigation with the exception of Sacramento River shipping to the city of Sacramento and on the San Joaquin River to Stockton, is practically non-existent. Small motorboats and rafting on the lower Klamath River and the summer boating and light freight and mail traffic on Lake Tahoe are of minor consequence. Recreational uses of the inland waters are confined mostly to the mountain lakes during three months of the summer season. In the extreme south, in San Diego County for example, where the reservoirs for public water supply are open for recreational purposes and the climate is milder, the use of these facilities are more extensive, the year round.

It is seen that water plays a very important part in the semiarid region like California and it is considered the most valuable asset of the land. Its unequal distribution calls for its wise administration, for large and costly engineering works, when it is necessary to transfer from one location to another, large volumes of water that the thirsty lands be given moisture. From the Mono watershed, now under development, to Los Angeles the distance is 600 kilometers. Tapping the Trinity River in the north into Sacramento river and transporting the water for use about Mendota means covering a distance of 800 kilometers.

To more specifically consider concrete problems the California State Water Plan and the Boulder Dam Project have been given considerable space. The former, as far as here treated, concerns chiefly the Great Central Valley, the most important agricultural portion of California and upon whose further development hangs the future of the region, has rightly been given some attention to show what is being done. The Boulder Dam Project means equally much to southern California, from there will come water for the orchards and fields and for a thirsty population as well as for growing industries. The development of this part of California is unparalleled and only the lack of water could stop its further progress. It is a blessed region with its fertile land and its sunshine when the moisture is on hand

to make things grow, without water it is quite worthless. As late as on the dawn of the century it was considered by many as worthless and could be given back to the Indians.

Law suits over water rights filed at the start of work on the Central Valley Project in California, spotlight the fact that legal problems are beginning to exceed engineering problems in efforts directed toward the utilization of the water resources of this region. California water law tends to present more problems than the clearer doctrine of prior appropriation used in other western states, but in general the situation is the same as in the other states of the arid West.

In the future there must be more emphasis on the legal and administrative efforts to secure equable distribution of supplies for the greatest common good. Continued progress of the West will force such action, although the trend of procedure and the logical agencies are difficult to predict. For example, in California much of the available water does not involve other states and the problems of relative value, priority and use are capable of solution almost entirely by state legislation and control. In the south-west on the other hand, a fourteen year old compact which was supposed to have provided the basis for the allocation of the water of the Colorado River has not proved a very effective basis. The real difficult problems of dividing the vital resource of the Colorado River water among the seven compact states of the basin remains unanswered after fourteen years.

Regarding the water resources of California in their geographical aspect, their occurrence, possibilities of conservation, their mode and location of utilization in various regions, the following facts are to be noted. Geographically we may divide California into the following regions each of which has its own character regarding the water resources and their present or future uses:

Cascade-Sierra Nevada Range:—These mountain ranges are the principal collectors and accumulators of moisture for the larger part of the productive land areas of California. Rainfall and snow cover in the higher regions furnish water for operation of the major portion of the hydroelectric power developments within the State. Storage reservoirs for power production are located at higher elevations, up to 3,300 meters, and the principal reservoirs for domestic water supply and for irrigation are located in the foothill and lower western slope region at from 500 to 1,000 meters elevation. Due to the comparatively flat slopes in the upper reaches of the rivers and to the soundness of the rocks the silting of reservoirs is slow in this region, a favourable factor in water storage and operation of plants. The region is sparsely settled and for construction operations often difficult of access causing high cost of development of the water resources.

Modoc Lava Plateau:—Located in the north-east corner of California this is a portion of the Great Basin from which the Pit River has sawed an outlet to the Great Central Valley bringing the better yielding water supply to the Sacramento River. The area is a continental high plateau land of about 1,400 to 1,700 meters elevation and forms a natural ground water

storage in the porous volcanic rocks. The plateau being limited in cultivable land and having a raw cold climate with short growing season does not require for local use all of its water resources and therefore a considerable part runs off to the Sacramento unused thereby accentuating the flow of that river for use in the Great Central Valley. In dropping to the valley level it produces hydroelectric energy in the Pit River and Hat Creek plants. This region also sparsely settled has for its main economic activities cattle ranging and lumbering.

Klamath Mountains:—The western slope to the Pacific Ocean is gentle but to the Great Valley to the east more abrupt. The west side receives ample precipitation and here grow the large redwood forests of California. The basins to the east are deficient in moisture and agriculture is carried on under irrigation. The water resources of the streams have to date been very little taken into use there being only small areas of cultivable land available. Export of water to the Great Central Valley has been given consideration in the State Water Plan to be affected by tunnelling the intervening mountain range thereby also offering opportunities for development of hydroelectric energy. The Klamath River has large potential power resources at present withdrawn from development, the stream being held in reserve for sport fishing and recreational use.

Coast Ranges:—These mountains furnish practically no water to the lands in the Great Central Valley, the streams all running toward the Pacific Ocean furnishing water to the fruit growing in the valleys to the north and south of San Francisco Bay. The region to the west is thinly populated but having a number of thriving communities in the valleys and around Monterey Bay on the coast.

San Francisco Bay Region:—This is the large population center of Central California. Many large cities have developed around the Bay and the fine harbour of San Francisco. The Bay also forms an outlet for the two large rivers the Sacramento and the San Joaquin both navigable to Sacramento and Stockton respectively. Industrial development here is the greatest in California, electric power, domestic and industrial water supplies being brought from the Sierra Nevada. From there and from the valley are brought many raw materials, fuel oil and natural gas are received from the southern end of the San Joaquin Valley about Bakersfield. The vegetable and fruit regions south of San Francisco Bay yield a large part of the food supplies to the nearby cities on lands irrigated mostly through pumped ground water and from smaller surface storage reservoirs.

Great Central Valley:—The fertile lands of the valley comprising two-thirds of all cultivable lands in California are capable of growing a wide range of products. Shortage of water was an obstacle until irrigation projects were established largely on a corporate or association basis and the completion of the Central Valley Project of the State Water Plan will bring the use of irrigation to greater perfection. A large number of cities and towns thrive within the borders of the valley.

Southern California:—The Coastal Plains and the Imperial Valley are highly productive areas with a large population living principally in a

number of cities of which Los Angeles is the metropolis. The mild dry climate, large cultivable land areas and the densely populated alluvial areas between the mountain ranges in connection with limited storage possibilities nearby make the water supplies from local sources insufficient for irrigation and domestic water needs. Importation of water from the Mono and Owens Valleys as well as from the Colorado River has been resorted to increasing the possibilities for still more intensive development. Large industrial development has taken place in the region which is also the center of the oil production in southern California. The region is occasionally visited by disastrous storms causing great loss of people and property. Colorado River water is also being counted upon for further development in and about the city of San Diego.

Great Basin:—The part of the basin within California is without an outlet to the sea and is mostly of desert character with many saline playas where mining activity is carried on. Wells supply part of the water for railroads, cattle and small gardening. The section is thinly populated, the agricultural activities having decreased during recent years since the groundwater supplies from the Sierra Nevada streams of the Owens and Mono watersheds have been appropriated and exported to the metropolitan area of Los Angeles. This region has of recent developed into a favoured recreation and tourist center.

In summing up the above discussion it is evident that the in nature varying physiographic regions of California complement each other functionally to one in many respect self-sustaining whole, especially in regard to hydrography. The Sierra Nevada, the Cascade, the Klamath mountains and the Modoc Plateau furnish little opportunity for cultivation and settlement, are however the collectors and accumulators of water and furnish hydroelectric energy and grazing areas as well as recreational ground during the summer months. The Great Central Valley, the San Francisco Bay region and the alluvial lands of Southern California having a warm and agreeable climate, large cultivable land areas and many possibilities for settlement must import water for irrigation and for domestic and industrial needs. The mountains are supplying water in abundance to the Great Central Valley and the Bay region. Southern California receives on the other hand a large portion of its water supply not only from other regions of California, but from the Boulder Dam, the Lake Mead Storage, which means from the rains falling in the Rocky Mountains.

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Errata.

- Page 12, l. 19 *stands* coefficiency
 read coefficient
- » 37, l. 25 *stands* Paris.
 read Stockholm.

CURRICULUM VITAE

I, Johan Valfrid Zahlén was born on November 27, 1881, in West Fernebo Parish, Province of Westmanland, Sweden. My parents were Johan Erik Sahlén, Builder, and his wife Mathilda, nee Sahlberg. I absolved the Public Schools and Continuation School, trained in the construction trades, studied at a Technical School of Engineering Design and Construction, and at the Stockholm Technical College. Graduated in Civil Engineering, (Tief- u. Wasserbau), at the Polytechnic Institute Strelitz, Strelitz-Alt, Mecklenberg, Germany, 1906. Studied at the Lane Technical High School, Chicago, Illinois, during the Winter Evening Terms 1912 to 1916. Instructor in Technical School 1903—04 and in 1908.

During the years of technical studies I practiced in the Engineering Profession during the summer months as draughtsman, surveyor and Engineers Assistant on Public Water Supply, Harbour, Canal, Railroad and Sanitary engineering projects in Scandinavia and in Germany. After graduation I followed Civil Engineering in North and South America until 1932, working in various capacities on design, construction, supervision of Water Power Developments, Harbour and Canal Projects, Industrial Projects for steam generation, metallurgical works, cement manufacturing works, pulp and paper mills.

In 1923 I was elected Member of the American Society of Civil Engineers, (M. Am. Soc. C. E.), in 1925 I became a Member of the American Society of Mechanical Engineers, (Mem. A. S. M. E.), and in 1930 I passed the requirements for Registered Civil Engineers in California. In 1932 I was honoured with the Competence Certificate for National Engineering Registration, valid in all States of the United States then having passed Engineering Registration Laws and which are Members of the National Council of State Boards of Engineering Examiners.

In the autumn of 1932 I registered at the University of Basle, Switzerland, studying principally Geology, Geography, Ethnology, Physics, Zoology and Statistics. During ten Terms I visited lectures and laboratory excercises with the following Professors:

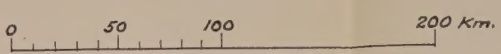
Prof. Dr. A. Buxtorf	Geology
Prof. Dr. J. Cadisch	Geology
Prof. Dr. F. Fichter	Chemistry
Prof. Dr. L. Furlan	Economics
Prof. Dr. A. Hagenbach	Physics
Prof. Dr. F. Jaeger	Geography
Prof. Dr. F. Mangold	Statistics

Prof. Dr. A. Portmann	Zoology
Prof. Dr. F. Speiser	Ethnology
Prof. Dr. P. Vosseler	Geography
Pdz. Dr. M. Reichel	Palaeontology

The present study, selected by myself, was started in 1934, when the months of August and September were spent in California for the purpose of collecting material and for going over the ground. The material was studied and sifted at the University of Basle, from autumn 1934 to the end of Summer Term 1936. The final writing and checking of the work was carried out in San Francisco, California, during the time from January to August inclusive, 1937.



SKETCH MAP OF
CALIFORNIA
SHOWING DAM AND RESERVOIR LOCATIONS



LEGEND	
Capacity Million m ³	Number
Upto 1	537
1-5	118
5-10	47
10-50	48
50-100	23
100-200	8
200-300	5
300-400	2
400-500	0
518	1
1611	1

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